2013

Development Of The Strategy To Select Optimum Reflective Cracking Mitigation Methods For The Hot-mix Asphalt Overlays In Florida

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DEVELOPMENT OF THE STRATEGY TO SELECT OPTIMUM REFLECTIVE CRACKING MITIGATION METHODS FOR THE HOT-MIXED ASPHALT OVERLAYS IN FLORIDA

by

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Sciences
at the University of Central Florida
Orlando, Florida

Spring Term
2013

Major Professor: Boo Hyun Nam

ABSTRACT

Hot Mix Asphalt (HMA) overlay is a major rehabilitation treatment for the existing deteriorated pavements (both flexible and rigid pavements). Reflective cracking (RC) is the most common distress type appearing in the HMA overlays which structurally and functionally degrades the whole pavement structure, especially under high traffic volume. Although many studies have been conducted to identify the best performing RC mitigation technique, the level of success varies from premature failure to good performance in the field.

In Florida, Asphalt Rubber Membrane Interlayers (ARMIs) have been used as a RC mitigation technique but its field performance has not been successful. In this study, the best performing means to mitigate RC in the overlays considering Florida's special conditions have been investigated. The research methodology includes (1) extensive literature reviews regarding the RC mechanism and introduced mitigation options, (2) nationwide survey for understanding the current practice of RC management in the U.S., and (3) the development of decision trees for the selection of the best performing RC mitigation method. Extensive literature reviews have been conducted to identify current available RC mitigation techniques and the advantages and disadvantages of each technique were compared. Lesson learned from the collected case studies were used as input for the selection of the best performing RC mitigation techniques for Florida's roads. The key input parameters in selecting optimum mitigation techniques are: 1) overlay characterization, 2) existing pavement condition, 3) base and subgrade structural condition, 4) environmental condition and 5) traffic level. In addition, to understand the current

practices how reflective cracking is managed in each state, a nationwide survey was conducted by distributing the survey questionnaire (with the emphasis on flexible pavement) to all other highway agencies. Based on the responses, the most successful method of treatment is to increase the thickness of HMA overlay. Crack arresting layer is considered to be in the second place among its users. Lack of cost analysis and low rate of successful practices raise the necessity of conducting more research on this subject.

Considering Florida's special conditions (climate, materials, distress type, and geological conditions) and the RC mechanism, two RC mitigation techniques have been proposed: 1) overlay reinforcement (i.e. geosynthetic reinforcement) for the existing flexible pavements and 2) Stress Absorbing Membrane Interlayer (SAMI) for the existing rigid pavements. As the final products of this study, decision trees to select an optimum RC mitigation technique for both flexible and rigid pavements were developed. The decision trees can provide a detailed guideline to pavement engineer how to consider the affecting parameters in the selection of RC mitigation technique.

ACKNOWLEDGMENTS

I would like to acknowledge the support of Florida Department of Transportation for generously funding this project. I am more than honored to be able to work on this project.

I would like to express my deepest appreciation to my adviser, Dr. Boo Hyun Nam, for his patience and guidance during these two years. Without his guidance and persistent help this thesis would not have been possible.

I am very grateful to my advisor and the thesis committee chair for reviewing the manuscript in spite of his very busy schedule and making several important suggestions which enhanced the edition.

I am pleased to extent greeting to other committee members, Dr. Amir Hossein Behzadan and Dr. Mehmet Omer Tatari for their valuable guidance and encouragements extended to me.

I wish to express my thanks to Mr. Fariborz Lachini and Mr. Yiruma for providing an inspiring and relaxing atmosphere during working on this study.

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CHAPTER 1: INTRODUCTION

1.1 Project Description

Reflective Cracking (RC) can be formed when a Hot Mix Asphalt (HMA) overlay is placed on jointed or severely cracked rigid or flexible pavements (see Figure 1.1). Creation of the RC on the HMA overlays can further develop other pavement distresses such as stripping and weakening sublayer materials (base, subbase, and subgrade) by allowing moisture infiltration. Therefore, there have been many attempts to prevent or retard the initiation of the RC on HMA overlay. The range of success for various projects is from failure to very successful depending on site condition along with a selected RC mitigation technique.

Florida Department of Transportation (FDOT) has been using an Asphalt Rubber Membrane Interlayer (ARMI) over nearly 20 years to reduce reflection cracking in the HMA overlays. Although the ARMI is a common RC mitigation method in Florida, the success of its field performance varies. Evaluating different projects in Florida, the effectiveness of ARMI's performance in terms of RC mitigation and instability rutting is still suspicious. A study shows that ARMI not only delay the RC initiation on pavements, but also increases the pace of RC appearance on the overlays. Moreover, several Florida state districts suspect the performance o ARMI in contribution to rutting (Green, 2012).

Given the inconsistent performance of the ARMI, there is a need to identify alternatives for replacing the primary RC mitigation method considering Florida's special conditions such as climate, binder and aggregate source, and top-down cracking.

Figure 1. 1 Joint Reflective Cracking

1.2 Research Objectives

The main objectives of this study are to understand the current practices of RC management and to identify the adequate RC mitigation method for the state of Florida. In order to achieve to this goal, the followings tasks have been accomplished:

- Conducting a literature review to understand the deficiency of the nationwide ongoing projects especially in Florida.
- Finding the key parameters in RC mitigation method performance.
- Developing a decision tree to select the most appropriate RC method to resist, control or delay RC in HMA overlay.

1.3 Research Scopes

Research scopes of this study are as following:

- Structural assessment of existing RC mitigation methods considering Florida's special conditions.
- Development of recommendations for the best performing RC mitigation methods.

Different methods of RC mitigation were identified through extensive publication reviews. The success level of each method was evaluated and key affecting parameters on crack initiation were identified. By studying Florida's current practices on the RC management and considering its special conditions (i.e., typical overlay type and climate), optimum RC mitigation techniques have been proposed to accommodate identified mechanism of RC initiation. A nationwide survey was also conducted to understand how other state manage reflective cracking and also to obtain inputs for selecting the potential RC mitigation alternative. For future work, conducting experimental tests is required to evaluate the proposed potential RC mitigation techniques on both rigid and flexible pavements.

1.4 Research Methodology

The research methodology involves literature reviews, nationwide survey, and the development of decision trees. Decision tree is the most adequate solution for RC at different distresses type and traffic circumstances. The objective of decision tree is obtaining the most accurate prediction possible for RC mitigation methods by providing a sequence of questions to find the solution. Thus, by applying conventional pavement system evaluation and considering the roads traffic condition, a decision tree could be established.

1.5 Organization of the Thesis

The following chapters of this thesis are shaped to achieve the aforementioned goals and objectives. Thus, the organization of the thesis is as follows:

Chapter 1: Introduction- This chapter describes the overview and objectives of the conducted research. Moreover, the study scope has been provided in this chapter.

Chapter 2: Literature Review- The focuses of this chapter are on the literature reviews in the areas of: 1) understanding the mechanism of RC in flexible and rigid pavements, 2) currently available RC mitigation techniques, 3) key affecting parameters on the development and propagation of RC, and 4) case studies of each mitigation technique used in the laboratory and field.

Chapter 3: Understanding FDOT Practices and Nationwide Survey- This chapter defines the framework of the study to achieve the aforementioned goals in the first chapter. Personal interviews and a nationwide survey on the RC management have been conducted. Historical approaches and current practice on how FDOT manage the RC mitigation were investigated. Moreover, Detailed and comprehensive analytical result of the survey is being presented in this chapter.

Chapter 4: Potential Reflective Cracking Mitigation Method Selection- In this chapter, RC mitigation methods have been proposed to be utilized on flexible and rigid pavements. Selections of the methods were on the basis of RC initiation mechanism and understanding of the material properties under Florida's special conditions.

Chapter 5: Decision Tree- Decision trees which have been developed for both rigid and flexible pavements are presented in this chapter. These decision trees are developed in the way to be used as a RC mitigation method guideline considering Florida's special condition.

Chapter 6- Summary and Conclusion: This chapter summarizes the conducted study on RC mitigation method. Later in this chapter a conclusion of the findings of the project has been presented.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Results of this study strongly stand on good understanding of the RC mechanisms and an extensive literature review. This chapter discusses about three main mechanisms of RC initiation and propagation in the HMA overlay. RC mitigation techniques will be categorized based on their type and RC retarding mechanism.

2.2 Reflective Cracking Mechanism

Reflective Cracking in asphalt pavement overlays occurs over the joints of existing underlying concrete pavement or structural cracks in Hot Mix Asphalt (HMA) pavements. It can also be created by traffic load or more generally, by differential settlement where the old and new layers meet. Moreover, RC can be initiated by expansion, contraction and bending from thermally induced movement of the layers. RC reduces the service life of the pavements by introducing premature deterioration of the pavement structure or other distresses that might be caused by water infiltration in the overlay (e.g., weakening the load bearing capacity of the base layer and loosing bonds between aggregates and asphalt binder).

The first process is mechanical cracking under traffic load when joints or cracks constitute differential vertical deflections. To be more concise, this mechanism of reflective cracking creates strain concentration in overlay. This strain may be result of bending or shearing action resulting from traffic loads. The second process is thermal cracking especially in locations with high daily temperature change. All these two processes result in cracks reflection in overlay when the local tensile stress surpasses the tensile strength of the HMA overlay (Fujie Zhou, Sheng Hu, Xiaodi Hu, 2009). The combination of shear and bending forces from traffic load and thermal force due to daily temperature changes can initiate RC on HMA overlays. Another common mechanism of RC in rigid pavements is slab curling which leads to top down cracking in the overlay. In the following sections, all the mentioned mechanisms will be discussed.

2.2.1 Crack Initiation under Traffic Load

Traffic load creates vertical movement in Portland Cement Concrete (PCC) slabs when Load Transfer Efficiency (LTE) in transverse or longitudinal joints or at the crack tips in HMA pavements is low. The differential vertical movement in joints or cracks depresses adjacent slab's ends resulting in shear stress in HMA overlay. The reflective cracking by traffic load is shear-fatigue phenomenon which is dependent on the magnitude of the differential vertical movement in joints or cracks. Thus, three important parameters which are more significant in this mechanism are (Von Quintus, 2009):

1) Magnitude of the wheel load
2) Amount of load transfer across the joints or cracks
3) Differential subgrade support under the slab

Reflective cracking in this mechanism is bottom-up distress and crack initiates from bottom of the overlay and propagates upwards. The schematic figure of this mechanism and its associating bending and shear loads are shown in Figure 2.1.

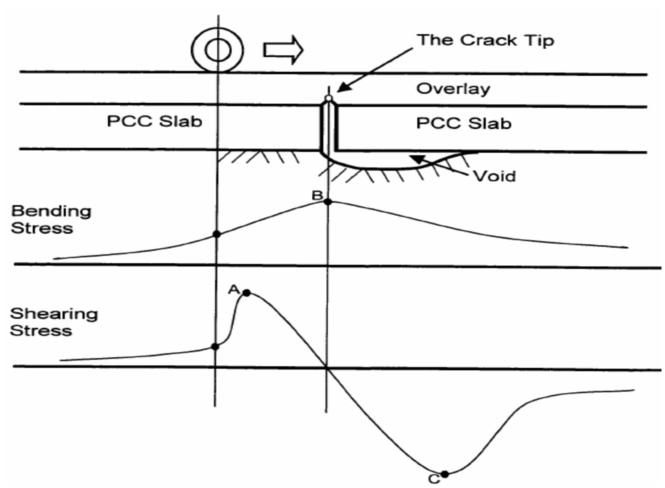


Figure 2. 1 Crack Initiations at the Bottom of the Overlay Due to Traffic Loading (Bennert, 2009)

2.2.2 Crack Initiation under Thermal Load

Thermally induced cracking occurs when temperature changes in existing pavement in a short period of time. Daily temperature change can result in expansion and contraction of layers and therefore results in horizontal movements. Tensile stress and strain at the bottom of the overlay due to the horizontal movements is a potential cause of initiation of RC (Figure 2.2). This type of cracking can be significant in regions with high daily temperature changes; however seasonal temperature change cannot be considered in this category. In seasonal temperature change, the overlay layer has time to adopt itself to elongations and shrinkages due to relaxation phenomenon in visco-elastic materials with respect to time. Development in thermal cracking dependent on the following parameters (Von Quintus, 2009):

1) Magnitude and rage of temperature change
2) Slab geometry
3) properties of the resurfacing material or overlay

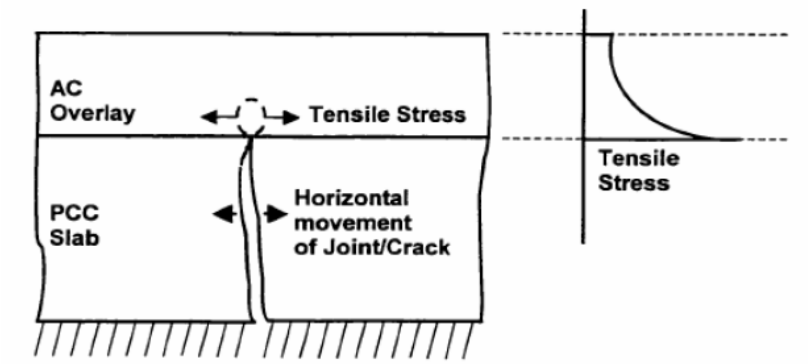


Figure 2. 2 Crack Initiation at the Bottom of the Overlay Due to Thermal Load (Bennert, 2009)

Figure 2.3 and 2.4 shows the vertical and horizontal slab movement due to daily temperature changes (Greene, 2012a). These figures show that by increasing daily temperature change, more movement in PCC slabs occur which result in higher tensile stress at the bottom of the HMA overlay.

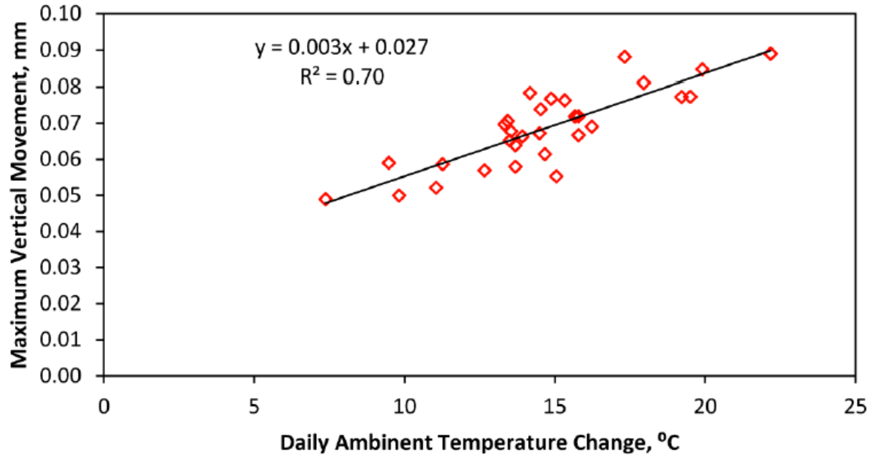


Figure 2. 3 Maximum Vertical Movement in PCC Slabs Due to Daily Temperature Changes (Greene, 2012a)

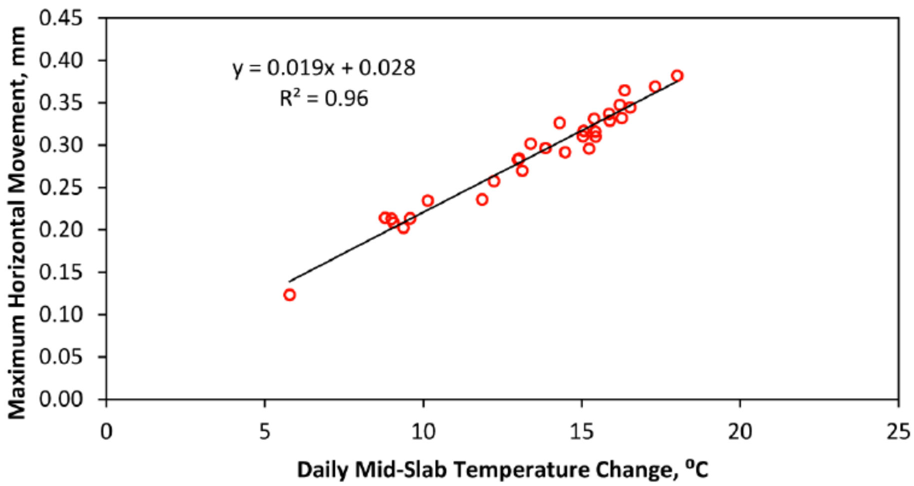


Figure 2. 4 Maximum Horizontal Movement in PCC Slabs Due to Daily Temperature Changes(Greene, 2012a)

2.2.3 Crack Initiation Due to PCC Curling

Thermal RC might be observed as bottom-up cracking or top-down cracking. Top-down cracking happens when layers start curling upwards as being described as the third RC mechanism. During the cold weathers, greater contraction at the surface causing PCC slabs curl up. When the adjacent slabs curl up, produces tensile stress at the surface of the overlay. Tensile stress at the surface, when HMA overlay is brittle enough, initiates cracking which propagates in shear in top-down direction (Greene, 2012b). Figure 2.5 shows the RC due to curling in PCC slabs which case top-down cracking in HMA overlays.

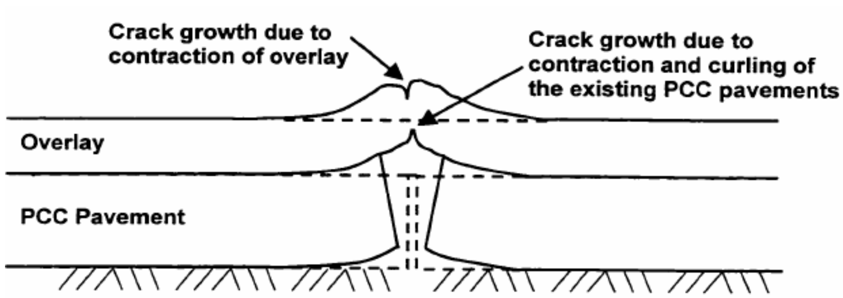


Figure 2. 5 Crack Initiation at the Surface of HMA overlay Due to Excessive Curling Load (Bennert, 2009)

In fact, considering only one RC mechanism as the only cause of crack initiation or propagation is not correct. Basically, RC in the field is induced by combination of the aforementioned mechanisms. RC can be prevented or retarded by applying appropriate methods of RC mitigation if exact mechanism of RC is being investigated.

2.3 Practical Reflective Cracking (RC) Mitigation Methods

In order to retard the RC on HMA overlays different approaches have been introduced which can be listed in five main categories as follows (Von Quintus, Mallela, Lytton, 2003; Mukhtar, 1996):

1) HMA Overlay Modification
2) Overlay Reinforcement
3) Stress Absorbing Membrane (SAMI)
4) Cushion Layers

2.3.1 HMA Overlay Modification

Improving material properties of HMA overlay can increase the resistance of the overlay to crack propagation. Treatment of asphalt overlay includes utilizing special mixture in the overlay. These mixtures can be rubber modified asphalt mixtures (AR), polymer modified asphalt (PMA) and stone matrix asphalt (SMA). In addition, increasing the overlay thickness can be included in this category.

AR mixture increases the viscosity and elasticity which can improve the resistance to surface initiated reflective cracking. Oxidation in HMA mixtures increase the brittlness and result in crack initiation. Basically, AR mixture is resistant to aging and oxidation due to rich binder content (thicker binder film comparing to conventional HMA mixtures) and anti-oxidant materials exist in tire rubber. Therefore, it is a good candidate to be used as one of the RC mitigation methods (Caltrans Report, 2003).

Use of PMA mixture in the surface course can help to improve the tensile and shear strength of the layer. Addition of polymer increases the resistance of the layer to environment and climate changes and increases the durability of the pavement (Mixes, 2007). Although the results are diverse, most of the results suggest that fillers or additives alone do no significantly delay reflective cracking, but are beneficial in keeping those cracks at a low severity for a longer period of time (Von Quintus, 2009).

The goal of increasing the HMA thickness is to delay the reflective cracking due to reducing the stress and strain in the thick overlay. However, by modifying the HMA overlay mixture, its properties are being improved so that it can resist higher stress and strain on the tips of cracks.

Increasing thickness of the HMA overlay reduces the load-associated damage by reducing the effect of poor load transfer across a crack or a joint in the underlying pavement, and thus, improve pavement performance. The greatest benefit from the use of thicker overlays on rigid pavements, however, is the ability of the HMA to insulate the PCC, reducing the amount of curling and temperature variations. Thicker overlay would be more beneficial when implemented on any type of transverse crack or joint because of the horizontal movements.

There are four main parameter to design and analyze HMA overlay system (Fujie Zhou, Sheng Hu, Xiaodi Hu, 2009):

1) HMA overlay materials,
2) Existing pavement condition,
3) Climate condition,
4) Traffic loading condition.

Based on the literature review, HMA thickness has a great influence on RC creation. Definitely, increasing overlay thickness can retard the RC observation on the surface of the overlay. HMA overlay can be implemented in single-layer or double-layer system while each layer can be made of different type of mixes and different asphalt binder types. Therefore, a wide range of combination can be used as a HMA overlay. HMA thickness can be determined based on its material's properties such as dynamic modulus, fracture properties and permanent deformation properties. As a rule of thumb, crack propagation rate in HMA overlay is about 1 inch per year (Thompson, 2008). However, a minimum overlay thickness should be considered when designing HMA overlay.

In a study (Amini, 2005), many case studies were compared to find the effectiveness of increasing surface asphalt layer thickness. In a case study, six sections consist of three sections treated by fabrics and different HMA overlay thickness and three sections without fabrics and different HMA overlay thickness were compared when implemented on existing Portland Cement Concrete (PCC) pavement. In both cases (with and without using fabrics) increasing the overlay by 2 inches delayed the observation of RC. In control sections, RC was observed in pavements with 2, 4 and 6 inches thickness after 1, 3 and 9 years respectively. This duration for treatment with fabrics for 2 and 4 inches was 3 and 6 years and for 6 inches section 60% of RC was not observed after 9 years monitoring. Figure 2.6 shows the effectiveness of employing thick HMA overlay on performance of fabrics in retarding the RC.

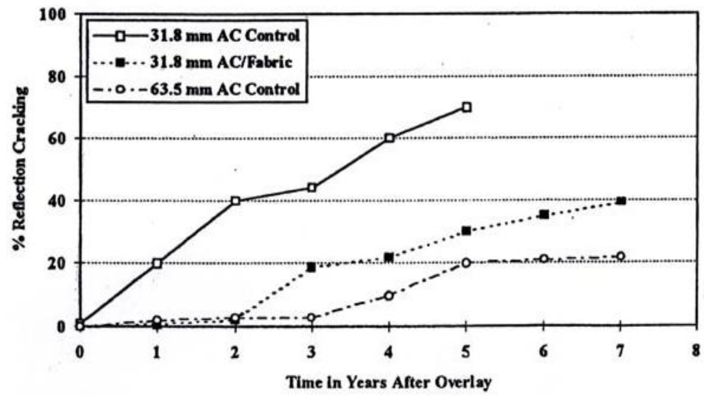


Figure 2. 6 Performance of Pavement for Various Pavement Thickness (Button1989)

From another point of view, different methods of treatment would not be successful when paved with insufficient overlay thickness (Carmichael, 1999). In an evaluation based on 30 different sites only 4 sites did not succeed in employing fabrics on existing Asphalt Cement Concrete (ACC) pavements. After further studying it was noticed that all the four sites were paved the fabrics with thin layer of overlay.

All things considered, only increasing the HMA overlay thickness would not be the best solution of mitigating the RC. Nevertheless, it can be highly useful when employing it with other types of RC mitigation methods.

2.3.2 Overlay Reinforcement

Asphalt pavement is basically having lower tensile strength comparing to its compression strength. Therefore, one of the prevalent methods of mitigation of RC is reinforcing the HMA surface layer using steel wire mesh or geosynthetics in parts with higher tensile stress. Steel reinforcement is consists of wire mesh and was used before using geosynthetics. By introducing the gyosynthetics, application of steel reinforcement was decreased. Reinforcing the HMA overlay not only increase the tensile strength of the pavement, but also prevents cracks from opening after occurrence.

2.3.3 Stress Absorbing Membrane Interlayer (SAMI)

Using low stiffness-highly flexible layer that can withstand large deformation can reduce the stress associated to the HMA overlay by dissipating excessive stress at the tips of cracks. Stress Absorbing Membrane Interlayer (SAMI) consists of a low-stiffness modulus material to dissipate higher fracture energy. This method of RC mitigation consists of small size aggregate combined with high binder content and low air voids. Chip Seal, Reflective Crack Relief Interlayer (RCRI), Asphalt Rubber Membrane Interlayer (ARMI) and Interlayer Stress Absorbing Composite (ISAC) are examples of this system. SAMI interlayer is normally 25mm (1 inch) in thickness (Von Quintus, 2009).

2.3.4 Cushion Layer

Cushion layers are thicker than SAMI interlayer (greater than 2 in.) and decrease the localized horizontal movements due to temperature change and slab curling movements. Due to the thickness, this interlayer structurally serves in pavement system . (Von Quintus, 2009). Moreover, as like as SAMI, resisting water infiltration is another function of this interlayer.

2.4 Reflective Cracking Mitigation Method Descriptions

In this section and before starting discussion about the literature reviews, two of the above RC mitigation methods will be described: Geosynthetics and SAMI. Geosynthetic method includes Geotextile (fabrics), geogrid, and geocomposite. SAMI method includes chip seal, ISAC, RCRI (or Strata) and ARMI.

2.4.1 Geosynthetics

Geosynthetics can be categorized as (1) geotextiles (fabrics), (2) geogrids and (3) geocomposites. Geosynthetics are being used to reinforce the overlay, relieving the stress and strain concentrations at joints or cracks, and reducing surface water infiltration in the lower layer (for geotextiles and geocomposites).

Fabrics or geotextiles may be woven or nonwoven and are typically composed of thermoplastics such as polypropylene or polyester but may also contain nylon, other polymers, natural organic materials, or fiberglass.

Geogrids may be woven from glass fibers or polymeric (polypropylene or polyester) filaments, or they may be cut or pressed from plastic sheets and then post tensioned to maximize strength and modulus. Grids typically have rectangular openings from ¼ inch to 2 inches wide.

Geocomposites generally consist of a laminate of fabrics on geogrids. For the composite, the fabric provides absorbency (primarily to hold asphalt) and a continuous sheet to permit adequate adhesion of the composite onto a pavement surface; whereas, the grid provides high tensile strength and stiffness. Manufacturers custom designed these third-generation products, based on laboratory and field research, to meet the needs of asphalt retention and high initial tangent modulus (Cleveland, Button, & Lytton, 2002).

2.4.2 Stress Absorbing Membrane Interlayer (SAMI)

SAMI is a low stiffness-high flexible material interlayer to withstand large deformation without breaking. Large deformation dissipates the stress on the top of the existing pavement and prevents it to reach to the HMA overlay. Another benefit of SAMI is its water protection characteristic which keeps the sublayers intact. As like as other interlayers, selecting a proper HMA overlay thickness is playing an important role in making the method successful.

Chip seal is a layer of asphalt binder covered by single size chips (around ¼ in.) which is being penetrated and compacted by a roller compactor. To have a more effective chip seal method in RC mitigation, this layer should be covered with partially thick HMA overlay. Chip seal prevents transferring of the existing cracks to the HMA overlay by its elongation and dissipating the horizontal strains.

ISAC is a composite made of a low stiffness geotextile at the bottom, a highly flexible bituminous material layer as a core and a high stiffness geotextile on the top to combine the effect of both geotexile and SAMI. The purpose of employing ISAC is to address the problems in RC distress on HMA overlays (Mukhtar, 1994; Dempsey, 2002). The crack movement can be effectively controlled when SAMI reduces the stress at the crack tips and geotexile can be served as an overlay reinforcement at the same time (Dempsey, 2002).

RCRI (or Strata) system is another type of SAMI which utilizing Styrene-Butadiene-Styrene (SBS) polymer Instead of using rubber. Figure 2.7 shows a sample of RCRI. RCRI consists of highly polymer modified asphalt binder and fine aggregates. High binder content makes layer more flexible and enables the layer to resist tensile stress and strain under thermal expansions and contractions. This interlayer is normally 25 mm (1 in) in thickness. Experimental results show the crack resistance improves by increasing the thickness and stiffness of the overlay and reducing the stiffness of the membrane layer (Von Quintus, 2009).

Figure 2. 7 Reflective Cracking Relief Interlayer or Strata (Pavement Performance Prediction Symposium, 2007)

ARMI consists of tear-off shredded rubber mixed in HMA and fine aggregates. Existence of rubber in the mix increases the elasticity of the pavement which leads to better performance in the term of RC mitigation. The high temperature causes elastomeric rubber polymer being mixed with asphalt binder, resulting in a stiff, elastic and flexible binder material that at low temperatures remains flexible and at high temperatures doesn’t flow. In a study in Arizona (Way, 1980) Asphalt Rubber outperformed conventional HMA when used on a cracked pavement and covered by 0.5

inches HMA course. However, shoving occurred and resulted in a rough surface. A profile of a system using ARMI interlayer is shown in Figure 2.8.

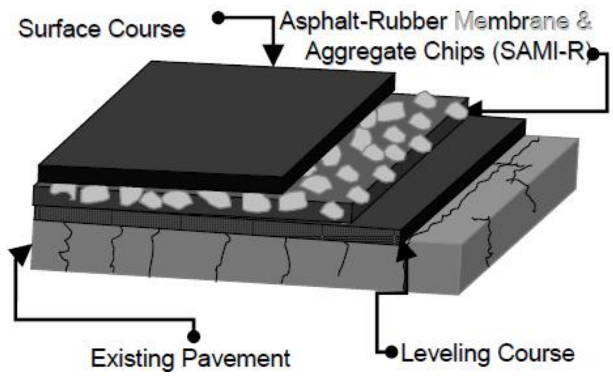


Figure 2. 8 Asphalt Rubber Membrane Interlayer in a Pavement System (Caltrans Report, 2003)

2.5 Case Studies: Field Performance

A variety of RC mitigation methods have been implemented in many states of the United States and wide ranges of results have been reported. The summary of the literature review is described in this section.

2.5.1 Nevada Study

Long-term performance of different techniques of RC treatments on flexible pavements was investigate in Nevada (Loria, Sebaaly, & Hajj, 2008). Data was collected by monitoring treated sections for fatigue, transverse and block cracking. Four methods were used on 33 different locations: cold in-place recycling (CIR), reinforced fabrics (RFs), stress relief courses (SRCs), and mill and overlay (MOL). For this study, the traffic level of each location has been expressed in Annual Average Daily Traffic

(AADT). Moreover, there is information about overlay design of each section. CIR projects with lowest and highest AADT were among the best performers after 6 years while two CIR projects with medium AADT experienced fatigue cracking after 3 and 7 years in service. While three out of six RF projects experienced reflective transverse cracking after 1 to 3 years, three of them did not experience any distress after 6 years being in service. RF projects with high AADT were among the worst performers. Performance of three RF projects with low AADT was acceptable. The SRC project with high AADT was experiencing no distress after 8 years in service while reflective transverse cracking was evident in two SRC projects with medium AADT after 5 years. Although only one MOL project performed well and without progress of any distress after 12 years, MOL projects were the only projects that experienced block cracking. Projects with this technique of mitigation with high AADT were performed poorly in MOL projects. However MOL treatment was effective in retarding the reflective cracking up to 3 years. Thus, it can be concluded that due to different range of performance even at the same location the performance of the reflective cracking treatment is highly dependent on *structural conditions of pavement* before applying the mitigation method. In addition, authors of the study ranked the techniques for Nevada's condition from best to worth as CIR, MOL, RF, and SRC.

2.5.2 Mississippi Study

In another study the effectiveness of fabrics (geotextiles) in retarding RC in flexible pavements was investigated (Amini, 2005). This study had extensive literature reviews on other state's experiences and conducted a survey for the practices in the Mississippi State. Four out of five districts in Mississippi had rare experience in using fabrics as stress absorbing interlayer. The survey results indicate that the overlay thicker than 2 inches or more increases the effectiveness of the treatment. In addition, the application of fabrics is more effective in warmer climate regions. In cold climates, fabrics can be effective in minimizes the freeze and thaw damages due to drainage capacity. Easy construction and low cost of the fabrics produce more benefit in the life-cycle-cost (LCC) analysis. It was recommended to use geotextile especially in warm climates (southern states). However, it is still effective because of its resistance to water infiltration when used in cold climates.

2.5.3 Arizona Study

Arizona Department of Transportation (ADOT) conducted a study on effectiveness of using SAMI, specifically Asphalt Rubber (AR), in retarding the reflective cracks on a very highly cracked concrete pavement (Way, 1990). They used 2 inches of AR and monitored the pavement condition over nine years. The location was very heavily trafficked interstate highway. The high temperature in summer reaches to 80°F and low temperature in winter is as low as -23°F. Five monitored parameters are crack percentages, International Roughness Index (IRI), rut depth, skid resistance, and maintenance cost. Before overlaying, concrete pavement was rehabilitated by crack-and-seat method that reduces the PCC slabs length to smaller pieces with 0.5-m spacing. A 2-in AR overlay was placed over 3-in of HMA that includes finer gap-graded mix. The results of field monitoring over nine years illustrate that all five condition parameters have been improved. The cost of the AR is about twice more expensive but the AR overlay requires less routine maintenance with better performance and its thickness can be the half of conventional HMAs.

2.5.4 Texas Study

A team from Texas Transportation Institute (TTI) worked on geosynthetics projects under HMA overlays to retard the effect of RC on pavements (Arif Chowdhury, Joe W. Button, 2009). They used geotextiles, geogrids and geocomposites as methods of treatment to reduce the severity or delay the appearance of RC. Three different locations were selected with cool, moderate and mild climate. The one with moderate climate was flexible over jointed concrete pavement (Waco) while two other locations were flexible pavements (Amarillo and Phar). Information about AADT, annual rainfall and average daily temperature range are available for each location. All test sections were monitored for transverse and longitudinal RC for five to six years. Due to milling large thickness of old pavement in Phar, a small percentage of reflective cracking was observed after six years and it was hard to make a conclusion about the effectiveness of treatment method on this section. In Waco, all treated sections performed better than control section. However, after 3.5 years of overlay construction, the rate of reflected cracks increased. It should be considered that pavements were treated on one-year old level up sections with reasonably high percentages of cracking. Treated sections outperformed the control section with respect to the fact that most of the sections had higher crack percentages than the control section before applying the treatments. In Amarillo the mitigation performance of most of the treatment methods were better compared to the control section. This study shows that new HMA overlay last longer when the old pavement is sealed before overlay while only applying level-up course does not increase the overlay's life. This section experienced the highest traffic load and maximum average daily temperature range compared to the other sections. What is in common for all test sections is increasing the rate of crack reflection after three to four years which may be due to deterioration of the in-service geosynthetic.

In another study conducted in Texas State (Chen et al.) Rolling Dynamic Deflectometer (RDD) and Overlay Tester (OT) were employed to evaluate the effectiveness of Rich Bottom Layer (RBL) and Stone Matrix Asphalt (SMA), both as SAMI interlayer, in retarding RC in jointed concrete pavements. In a project, 1 inch of RBT layer applied after milling full depth of old HMA and repairing JCP pavement. 3.5 inches of HMA overlay covered the RBT layer at the end of the rehabilitation. Based on RDD results, pavement's structural condition improved after milling. The milled HMA was in poor condition with only 2 cycles of OT test. Considering the poor condition of the pavement condition, RBL was successfully performed with no visible RC after 3 years.

On the second project a 3-inch of SMA was paved on structurally moderate Continuously Reinforced Concrete Pavement (CRCP) after repairing it. Result of the RDD test run on the rehabilitated section was very good and OT results on core samples exceeded 700 cycles. The rehabilitated section's performance was excellent with no visible cracks after 5 years. These two projects indicate the importance of placing thick HMA overlay on RC mitigation methods and the structural condition of the existing pavement before overlaying.

2.5.5 Alabama Study

In a study conducted for Airfield Asphalt Pavement Technology Program (Von Quintus, 2009) different RC mechanism have been discussed for overlay on both PCC and HMA pavements. In this study, thermal cracking has been identified as one of the main cause of RC which is dependent on magnitude and rate of temperature change, slab geometry and property of overlay materials. In addition, curling in PCC slabs is another thermally induced cracking mechanism which is prevalent in cold climates or when HMA surface is aged or brittle. In this crack mechanism crack initiates from surface of overlay and propagates downward to thermal joints in the PCC pavements. The third crack mechanism is caused by differential vertical deflection in joints. In PCC pavements with low Load Transfer Efficiency (LTE) between slabs, wheel loads make large vertical deflection in PCC joints proportional to magnitude of the load. The deformation is depended on the amount of load transfer and differential subgrade support under the slab.

In this study, structural assessment of existing pavement before selecting the proper mitigation method has identified as one of the key factors for success of the mitigation method. Afterward, if needed, modification of existing pavement should be implemented based on condition and type of the existing pavement. Different RC mitigation methods have been introduced and discussed in this study. For instance, the performance of geosynthetics in mitigating RC in HMA overlays has been discussed and its success has been classified from successful to failure. Specifically, the success of geotextile performance was suspicious when it is applied on Jointed Reinforced Concrete Pavement (JRCP) and Jointed Plain Concrete Pavement (JPCP), and when large differential vertical deflections and faulting occur at joints and cracks. Moreover, It was concluded that paving fabrics on flexible pavements has little benefits for thin overlays (less than 2 inches), but for thicker HMA overlays, its performance was mostly successful.

2.5.6 Illinois Study

A study conducted in Illinois (Baek, Al-Qadi, Xie, & Buttlar, 2008) to identify the effect of utilization of interlayer systems in RC mitigation in PCC pavements. SMA and ISAC interlayers were used in this project. Ground Penetration Radar (GPR) was used before and after implementing treatments to locate joints, patches, dowel bars and other discontinuities in existing pavement. In addition, with the aim of high-quality video camera existing cracks were detected in pavement to map it over GPR photos to find reflective transverse cracks. SMA section was a 1.5-inch HMA consisted of sand size aggregate and 8% PG 76-28 fiber modified asphalt binder, topped with 1.5 inches of dense graded HMA. ISAC sections were treated with 90 cm-width ISAC layers on transverse joints topped with 2.25 inches leveling course and wearing HMA course. SMA was implemented on Jointed Reinforced Concrete Pavement (JRCP) while others were placed on Jointed Concrete Pavement (JCP).

RC appearance ratio was defined as the ratio of total number of reflected cracks to total number of joints patches and existing cracking. Considering this parameter, ISAC section lasted longer than others with 50% RC after 2.5 years. However, this ratio is insufficient to represent reflective crack's extent and severity. Thus, RC appearance ratio with weight function was defined as the combination of quantity and severity of RC. Considering both severity and quantity of cracks in JCP pavement, ISAC provided relatively better performance after 6 years of crack monitoring; while SMA interlayer retarded reflective cracks in JRCP pavement comparing to control section for 2 years of monitoring the section.

Another study conducted in Illinois in 2004 and compared the effect of utilizing RCRI on rigid pavements at five different states (i.e., Illinois, New Jersey, Virginia, Missouri and Kansas). In all the cases the thickness of the RCRI was 1 inch followed by 3 to 4 inches of HMA overlay. Control sections were conventional HMA overlay with the thickness of 4 to 5 inches. In all sections RCRI sections outperformed the control sections (Blankenship, Iker, & Drbohlav, 2004).

Further studies on control sections were conducted to investigate the effect of site condition on reflective cracking on HMA overlay. By plotting the traffic condition, overlay thickness, structural strength of existing pavement, PG type of asphalt binder and minimum flexural stiffness of RCRI layer versus average crack propagation per year, it was concluded that traffic load and overlay thickness have insignificant relationship with the RC propagation. Furthermore, it was indicated that to have a successful RCRI treatment, the layer should meet the minimum flexural life of 100,000 cycles.

2.5.7 New Jersey Study

In another study, a nationwide survey distributed over all transportation DOTs to evaluate the current condition of rigid and composite pavements after applying reflective cracking mitigation methods (Bennert & Maher, 2007). Finally, 28 out of 50 states turned the questionnaire. In this survey, two out of 28 states did not have rigid or composite roads.

The results showed that 85% of respondents were observed reflected cracks within the first 4 years after HMA overlays and 27% of them observed it within the first 2 years. They found out that there is no trend between reflective cracking and base course type (e.g., granular base, cement base, lime base and bitumen base). The same conclusion could be made for joint spacing and shoulder type (e.g., HMA, PCC tied and PCC untied).

Moreover, they divided the country into different zones based on the minimum air temperature, recommended by LTPPBind program. Considering the type of asphalt binder which each states uses, it was determined that when the difference between the in-service low temperature performance grade and the LTPPBind recommended low-temperature performance grade is higher, the HMA overlay will last longer before observation of RC. Table 2.1 shows the significance of time to appear RC on the overlay. Furthermore, the most prevalent mitigation method in the Unites States is geotextile which is, surprisingly, have the weakest performance in crack mitigation experiences with 11.5% success. SAMI was the most successful method with 35% success which is very low to be considered as the best method.

Based on the recent survey, Bennert et al. utilized 1 inch of RCRI topped with 3.5 inches Superpave HMA on Illinois PCC roads (Bennert, Worden, & Turo, 2009). To measure the structural condition of the existing pavement (e.g., LTE) Falling Weight Deflectometer test was utilized. All sections were in good structural condition before applying the mitigation method. Moreover, measured Dynamic Modulus of the mixture shows that the RCRI mix has intermediate and low-temperature (intermediate to high loading frequencies) stiffness much lower than that of the Superpave mix. In addition, TTI and Flexural tests indicated that fatigue life of RCRI is much higher than conventional Superpave mix.

Table 2. 1Performance Grade of Asphalt Binder and Reflective Cracking Life of Different States (Bennert & Maher, 2007)

State	LTPPBind	Binder Used	Reflective Cracking
North Dakota	-34 °C/ -40 °C	64-34 over 58-28	1 to 2 yrs
South Dakota	-34 °C	64-34 or 64-28	1 to 2 yrs
Kansas	-22 °C/ -28 °C	70-22	1 to 2 yrs
Arkansas	-16 °C/ -22 °C	76-22	2 to 4 yrs
New Jersey	-22 °C	76-22	2 to 4 yrs
Ohio	-28 °C	70-22 over 64-28	2 to 4 yrs
Florida	-10 °C	76-22	> 4 yrs
Texas	-10 °C / -16 °C	76-22 or 64-22	> 4 yrs

Considering the existing pavement condition, early cracking was observed after 6 month of implementation of the RC mitigation method. Coring from in-situ treated pavement showed that there is insufficient bond between the surface and bonding coat and insufficient thickness of RCRI in cracked areas. Therefore, a new TTI test was conducted based on as-built thicknesses. Result of the new test indicated a significant difference between the fatigue lives of reduced and designed-thickness systems utilizing RCRI interlayer.

2.5.8 Worldwide comparison study for fabrics

In another study an intensive literature review was conducted to find the effect of fabrics on retarding the reflective cracking in PCC and HMA pavements (Carmichael, 1999). Four different treatments at different locations were compared as follow:

1) Paving fabric with a chip seal over unpaved roads and subgrades (Case1)
2) Paving fabric and chip seal over existing ACC pavements (Case 2)
3) Paving fabric and ACC overlay over existing PCC pavements (Case 3)
4) Paving fabric and ACC overlay over existing ACC pavements (Case 4)

Considering Case 1, all the literatures indicated successful experiences in applying fabrics and chip seal during monitoring periods of the pavements. Case 2 was not successful in all of the locations which higher traffic load might be the reason when it is being compared with the case 1. Results for case 3 shows that using fabrics on PCC pavements can retard the development of reflective cracking; however, it is not completely effective in combating the reflection of existing transverse cracks or joints when there is excessive vertical movement or high deflection on the existing pavement. Thirty sites were evaluated in this literature review as case 4. Twenty six of them found out that using fabrics effectively resulted in retarding reflective cracks while other four sites reported that insufficient overlay thickness resulted in early crack observation.

Based on reviewing different case studies in this study, overlay thickness should be carefully designed to get the most advantage from the paving fabrics. In a study in Georgia 60% of RC was observed after 3 years in pavement with 2 inches overlay and 6 years with 4 inches overlay and not being seen during 7 years of monitoring (Less than 20% after 5 years of monitoring).

2.6 Application of Decision Tree in RC Mitigation Studies

2.6.1 Why Utilizing Decision Tree?

Using decision tree, multiple variable analysis can be performed. The multiple variable analysis enables users consider influence of several parameters on a certain problem. In this project, key parameters on the performance of the mitigation method will be considered as variables in the decision tree.

Many multiple variable techniques are available. Decision trees are an appealing technique due to their relative power, ease of use, robustness with a variety of data and levels of measurement and ease of interpretability. A strong relationship between input values and target values in a group of observations can be formed by using a decision tree. This relationship forms a branch when a set of input values is identified as having a strong relationship to a target value, which can be grouped in a bin (De Ville, 2006).

On the other hand, decision tree has capability of grouping quantitative and qualitative inputs in a branch. In the case of RC mitigation method, existing pavement's structural condition and traffic level are qualitative and quantitative inputs respectively which can be grouped in a branch.

2.6.2 Decision Tree in RC Mitigation Method's Managements

In a study conducted for Airfield Asphalt Pavement Technology Program (Von Quintus, 2009) different RC mechanism have been discussed for overlay on both PCC and HMA pavements. The research methodology of this research is utilizing decision tree to find the best solution for 1) existing pavement treatment and 2) RC mitigation method. The solutions are based on existing pavement condition evaluation without considering any other parameters.

In another study conducted in New Jersey, a decision tree was developed to address the RC on rigid pavements. Utilizing structural condition evaluation of the existing pavement and forensic information led to decision tree methodology that would allow state agencies to properly select asphalt mixtures for overlaying PCC pavements (Bennert, 2009).

Moreover, a decision tree was developed in Virginia to address the rehabilitation treatments of HMA overlays over flexible pavement. The decision tree covers extent and severity of distresses by investigation and forensic evaluation of the pavement to predict the final solution of HMA treatment (Hicks, 2000).

2.7 Result of Conducted Survey for RC mitigation on Rigid and Composite Pavements

For better identification of crack reflection mechanism and predicting its performance, effective parameters need to be clearly identified and the effect of each parameter should be well understood. Bennert (Bennert & Maher, 2007) conducted nationwide survey to identify the current RC mitigation practices of HMA overlay over composite/rigid pavements. Fifty states were contacted and only 28 state agencies replied. The New Hampshire State does not build a jointed concrete pavement (JCP) and the New York State does not place overlay over the JCP. General elapsed time of reflective cracking observed for each state are presented in Figure 2.9. Based on the survey result, the identified parameters are: (1) base course type, (2) shoulder type, (3) joint spacing, (4) sawing and sealing joints, (5) Hot Mix Asphalt (HMA) overlay design method, (6) HMA materials (binder and aggregate), (7) site condition (i.e., climate, traffic, and soil conditions).

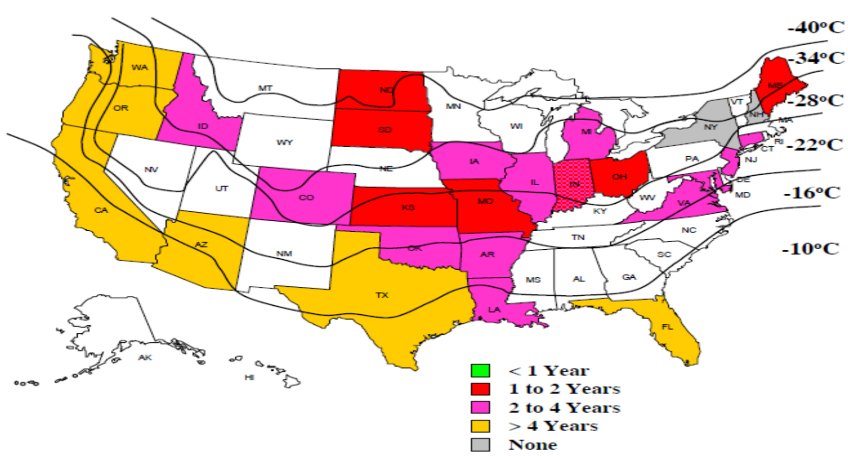


Figure 2. 9 Time reflective cracking observed after placement of HMA overlay (Bennert & Maher, 2007)

2.7.1 Type of Base Course

The reported types of course materials were aggregate, cement treated, bituminous treated, lime stabilized, or none. There was no correlation found between the type of base course and reflective cracking, but in general most of the responding states use granular base courses.

2.7.2 Shoulder Type

The commonly reported types of shoulder include PCC or composite pavements, with an HMA overlay, were HMA, PCC (tied) and PCC (untied). The majority of the states reported HMA and untied PCC shoulders. However, no trend was established relating the shoulder type and the reflection cracking.

2.7.3 Joint Spacing

Vertical or horizontal joint or crack tips movement influences RC performance on HMA overlays. Joint spacing may affect the joint movement. Most states reported that the joint spacing is about 15 ft in length; but no trend could be made from the responses.

2.7.4 HMA Overlay Design Methods

20 of the 26 states reported the use of 1993 AASHTO Design Guide/DARWIN to base the thickness of the HMA layer; however, most of these states have in place a minimum HMA thickness that must be met regardless of the design guide. 6 of the 26 states report a standard minimum thickness policy for HMA overlays which must be met.

The minimum thickness policy is based on past history, traffic and pavement conditions, pavement geometry and the cost.

2.7.5 HMA Overlay Materials

Most states reported that they place either 9.5mm Superpave mix or 12.5mm Superpave mix HMA overlay. Some states, however, have developed the use of unique mixtures to utilize in their state. A trend was developed with respect to the PG grade binder used by the states and the time of first signs of RC observation. The PG binder grade used by the different states typically corresponds to that recommended by LTPPBind. Figure 2.10 developed with 98% reliability shows the LTPPBind recommendations versus the time to first observed cracking in the HMA overlay.

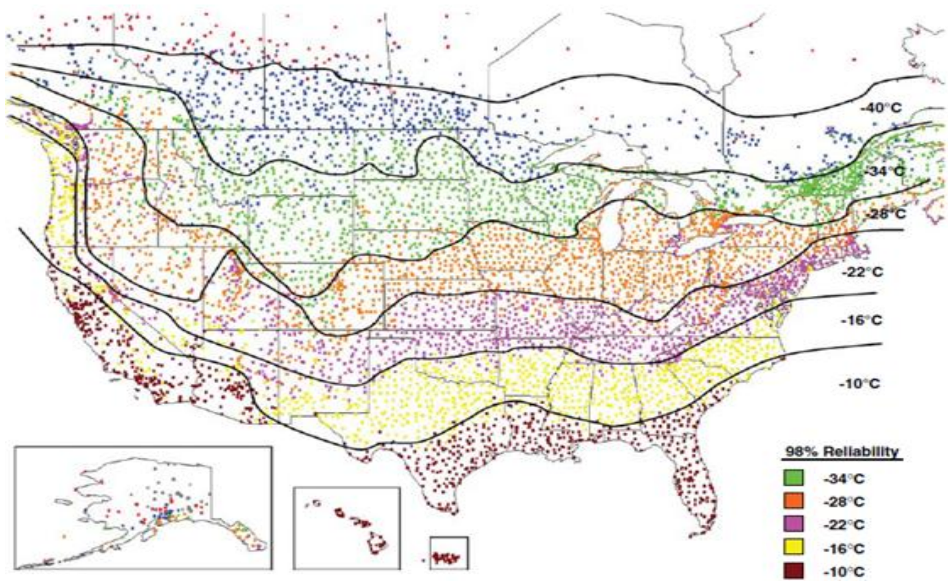


Figure 2. 10 LTPPBind recommendations for low-temperature performance grade at 98% reliability (Bennert & Maher, 2007)

2.7.6 Site Conditions

Proper knowledge of structural condition of in-situ pavement is valuable information that enables a pavement engineer to make a cost effective design. In the case of designing an HMA overlay over aged JCP, the following information are required; (a) vertical deflections at joints/cracks, (b) load-transfer efficiency (LTE) of joints/cracks, (c) in-situ pavement thickness, (c) modulus/strength of supporting material (base, subbase, subgrade), (d) traffic counts/vehicle classifications, (e) visual distress information and (f) laboratory testing.

2.8 Conclusion

Chapter 2 discussed about potential mechanisms of RC initiation and propagation on HMA overlays. Crack initiation under traffic load, under temperature load, and due to PCC curling are identified as the most common mechanisms of RC occurrence. It was concluded that crack initiation could be result of combination of two or all of them.

Furthermore, characterization of two types of mitigation methods, geosynthetics and SAMI, were discussed. It was understood that geosynthetic materials work under tension stress, while SAMI is good in dissipating stress due to its high flexibility. Under the category of SAMI, several treatment methods were introduced. Chip seal, ISAC, RCRI ARMI and SMA are having the same material characterization and could be utilized for as RC mitigation method before placing HMA overlay.

Finally, current in-field practices of RC mitigation techniques were discussed. The in-filed success level of each project was evaluated from premature failure to good performance. It can be concluded that there are several parameters which can impact the performance of the applied mitigation method. Other than construction quality, which is assumed to be at a certain level, the most effective parameters (key parameters) will be discussed in the Chapter 4 of this study.

CHAPTER 3: UNDERSTANDING THE FDOT PRSCTICES AND REFLECTIVE CRACKING SURVEY RESULTS

3.1 Introduction

After reviewing past practices of RC management in other states, FDOT practices will be discussed in this chapter. ARMI is one of the most utilized materials in Florida for addressing the RC distress on HMA overlays. However, based on the literature reviews on Florida's practices and conducting personal interviews by FDOT pavement experts, its deficiencies have been introduced.

In addition, a nationwide survey was conducted to understand the most recent practices of RC mitigation management in all the state highway agencies in the United States. This survey was focused on the performance of RC mitigation methods on flexible pavements in different states. In another study, Bennert and Maher (Bennert & Maher, 2007) conducted a survey on rigid and composite pavements. In this study, the survey questionnaire was developed through the discussion with FDOT pavement engineers prior to the survey distribution. Method of surveying was web-based and distributed through the FDOT to the other state highway agencies. The questionnaire was composed of 14 questions considering duration of the pavement from new placement to the first RC observation, type of RC mitigation method being used, criteria for selecting the RC mitigation technique, success of the technique, life expectancy of the treated pavement, existing pavement evaluation techniques, rehabilitation treatments on the existing pavements prior to applying the RC mitigation method, HMA overlay design method and cost consideration.

3.2 Review of Florida DOT Experiences

In January 1998, the FDOT conducted a study in Baker County on SR 2 to evaluate the long term performance of ARMI on five unique test sections of the eastbound lane of the road. Results of deflection, ride quality, rutting and cracking for treated sections were obtained. Out of the five test sections, test section 1 and 2 incorporate the use of ARMI where test section 3, 4, and 5 did not utilize it. From the 2011 results, section 1 has the largest depth of rutting of about 0.24 inches as well as the most cracking at about 225 SF/1000 SF of cracking. Section 1 also shows a substantially larger amount of transverse cracking over the other four sections at about 27 SF/1000 SF or transverse cracking (FDOT ARMI Report, 2011).

The original roadway of SR 10 was constructed in the late 1920's and has a 7-inch PCC and unpaved shoulders. After several rehabilitation efforts the roadway was expanded from 2 lanes to 4 and reflective cracking has been observed in the two inside lanes. The purpose of this study was to explore the effectiveness of alternate methods to counter reflective cracks from occurring. The study was on five sections with the length of 1,368 feet and included the eastbound (2 lanes) and westbound (2 lanes) directions. The project was completed in January of 2010. RC mitigation methods used for this project consisted of 1 inch Open-Graded Crack Relief (OGCR) in section 4, 0.5 inch ARMI in section 5, 6 inches of Sand Asphalt Hot Mix (SAHM) to replace 6 inches of existing base in sections 1 and 4, and the combinations of different thicknesses and materials in all test sections. The performance is evaluated based on deflection, cracking, rutting, and ride quality. As of 2011 results were obtained, and with respect to the cracking observations, test sections 5 and 3 in the west bound traffic lane showed the highest quantity of cracks equaling 26.59 and 13.29 SF/1000 SF of cracks respectively. No cracks were observed in either of the eastbound lanes (FDOT Crack Relief Report, 2012).

In 1994, the use of a geogrid in pavement systems was started on state road 80 in Palm Beach County. Two test sections of 1000 feet in length were constructed to evaluate the use of a geogrid and finding its effects on deflection, ride, rutting and cracking. Both the eastbound and westbound directions were used. The westbound lane remained in use as control section and had no geogrid, while geogrid was utilized on the base layer of the eastbound lane. The most recent results from October 2005 show that the use of the geogrid reduces the rutting depth but an increase of cracking develops when compared to the control section. The ride number for both eastbound and westbound lanes have been recorded at about the same numbers throughout the testing period and shows no apparent advantage of geogrid usage (FDOT Geogrids Report, 2005).

A study was initiated in 1999 to evaluate the performance of geogrid and geotextile as base and subbase reinforcement layers in pavement systems. Deflection, ride quality, rutting and cracking were measured to evaluate the performance of these two methods. This study is ongoing and was constructed on state road 15 in Palm Beach County. Five test sections of roadway were constructed using various combinations of geosynthetic materials such as rigid and flexible geogrid, and woven geotextile. Each test section used a combination of two geosynthetic materials mentioned above in different layers, except for section 5 which did not utilize any geosynthetic material and acts as a control section. From obtained results, most sections which employed any combination of geosynthetic had better performance compared to the control section without any geosynthetic material. From the September 2011 results, cracking found on the northbound lane were higher in the control section; however, cracking in the southbound lane exceeded that in test section 1 (FDOT Geosynthetic Reinforcement Report, 2011).

In a study conducted by the University of Florida (Y. Chen, 2012), 3 specimens with ARMI layers and 3 control specimens were tested in the laboratory to evaluate the effectiveness of ARMI in controlling RC on HMA overlay by employing Composite System Interface Cracking (CSIC) system. It was found out that specimens with ARMI failed after 175,000 cycles of loading while the control specimens failed after 220,000 cycles. This cycle for control specimens were 220,000. They concluded that ARMI not only decreases the overlay resistance to RC, but also accelerate the process of cracking. They also indicated that AR does not have the same capability of polymer modified asphalt binder to dissipate the stress at the interface of interlayer and overlay.

3.3 Personal Interview with Pavement Expert

The objective of this section is to better understand the FDOT RC mitigation management and Florida's special conditions. Several pavement engineers in the groups of pavement evaluation and material were interviewed to understand: (1) how the FDOT has managed the reflective crack, (2) how the FDOT has evaluated the surface distress, (3) what are special conditions in Florida, (4) what mitigation treatments have been used in Florida, and (5) what lessons learned from the FDOT ARMI study. Summary of discussions and findings are presented below:

- The majority of Florida's state maintained road is asphalt pavement. Asphalt and concrete pavements are approximately 98% and 2%, respectively in Florida. Considering the different mechanism of reflection cracking depending on the pavement type, the focus needs to be placed on the reflective cracking mitigation in asphalt pavement.
- In order to prevent pavement rutting, higher viscosity of asphalt binder is commonly used in Florida (PG 76-22). Despite the high temperature during summer in Florida, rutting is not a critical problem but surface cracking (top-down cracking) is more significant.
- Over 90% of cracking in Florida is top-down cracking rather than bottom-up cracking. The mechanism of top-down cracking can be explained by thermal effects (temperature gradients, thermal stress), loading effects (tension induced by truck tire ribs), and aging effects (binder hardening). The top-down cracking is commonly developed in the form of longitudinal cracking along wheel paths.
- Asphalt rubber membrane interlayer (ARMI) is most often used when cracks cannot be entirely removed during milling. Top-down, bottom-up,

and full-depth crack in the underlying pavement may cause different stress distribution at the bottom of new overlay.

- ARMI is less stiff materials than typical HMAs. When the ARMI is placed closer to the surface, it undergoes higher compressive stress due to traffic loading, resulting in greater rutting. Considering the stress distribution, a proper depth should be determined for the ARMI so that stress applied to the ARMI can be minimized.
- Annual precipitation in Florida is higher than other states. The moisture effect in HMAs along with aging may affect reflective cracking developed in the HMA overlay.
- Visual survey easily identifies reflection cracking in the AC overlay over JCPs because most reflective cracks appear at joint locations but it is not clear whether it is reflection cracking in the AC overlay over HMAs unless condition survey is carried out before and after the overlay placement.
- Subgrade soil settlements due to organic soils and sinkholes are common in Florida. These differential settlements may cause surface distress in pavements. However, the problems below the subgrade layer are not considered in this study (out of scope).

3.4 Survey Questionnaire

A nationwide survey was distributed to be responded by state transportation agencies. The focus of this survey was on RC performance and management in all the states. Table 3.1 presents the survey questionnaire. Detailed responses to the following questionnaire have been provided in Appendix A.

3.5 Survey Results

Total of 17 states have responded for the RC survey. To get the better understanding from current practices of other states, it is necessary to receive more responses from other states. More significantly, Florida's peer states in term of climate have still not responded to the survey. By having complete survey result a better insight will be provided. Responded states are shown in Figure 3.4.

Based on the results, all the responded states have experienced RC on their roads. None of the states expect RC appearance in the first year of construction as see in Figure 3.1. Only 2 states (Washington and Nevada) expect their roads last longer than 4 years without significant RC.

Table 3. 1 Reflective Cracking Management Survey Questionnaire

Number	Questions
1	Have you noticed reflective cracking on hot mix asphalt (HMA) overlays over flexible pavements when reflective cracking mitigation methods were not used?
2	In this case, what's the typical thickness of the HMA overlay (Inches)?
3	How soon after placement of the overlay does the reflective cracking appear?
4	Have you used any mitigate reflective cracking methods? If so, please comment on its field performance.
5	Why were the above mitigation methods selected?
6	What criteria were used to determine appropriate reflective cracking mitigation methods?
8	Based on field experience, which reflective cracking mitigation method has been the most successful in your state?
9	When using the best performing mitigation method, what is the performance expectation? In other words, how much longer do you expect it to last before reflective cracks appear?
10	Prior to designing the HMA overlay for a flexible pavement, what pavement tests and measurements are conducted for designing appropriate reflective cracking mitigation techniques?
11	What treatment(s) are typically used to prepare the existing flexible pavement before placing the HMA overlay?
12	For HMA overlay design, do you use a design method/guideline or simply use a minimum thickness? (Typical/minimum thickness description: e.g., 5 inches of HMA – 2 inches of 12.5 mm PG 76-22 over PG 76-22 over 3 inches of 19 mm PG 64-22)
13	What constitutes criteria for a successful reflective cracking mitigation method? (in terms of improved performance, percentage reflected cracks, or both) Example: 50% of the reflective cracks appear after two years.
14	Do you consider life-cycle cost for each mitigation method?
15	How much is the unit cost of the method (per lane-mile)?

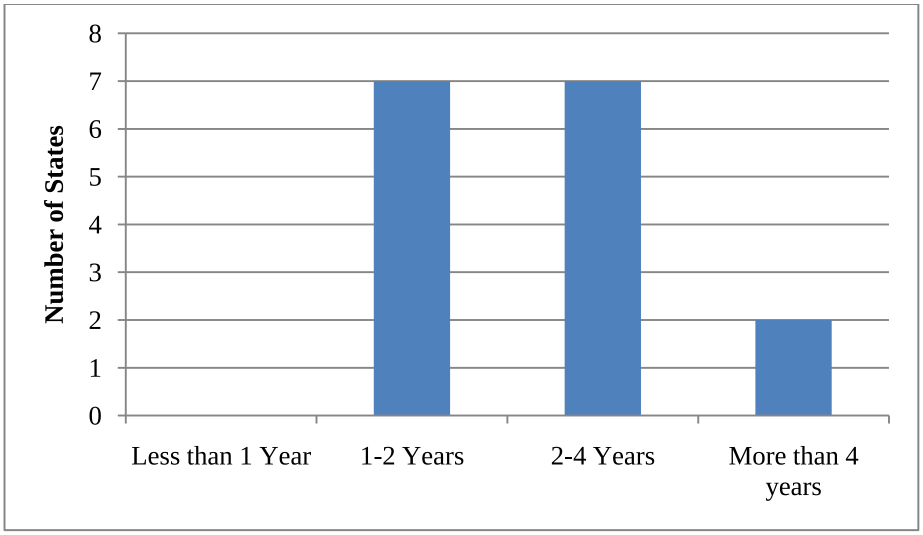


Figure 3. 1 Time to Appear Reflective Cracking after the Placement of New Overlay.

All DOTs mentioned that they have installed and evaluated more than one RC mitigation method. The survey responses on how to select the RC mitigation method indicates following criteria: 1) research, 2) on a trial basis, 3) cost, and 4) installation pace. Table 3.2 summarizes the criteria for each state DOT.

Table 3. 2 Selection Method of Reflective Cracking Mitigation Techniques

State	**Reason for Selecting the Method**
Illinois	Research
Alaska	Rapid Instalation
Idaho	Research
Iowa	On a Trial Basis
West Virginia	On a Trial Basis
Washington	On a Trial Basis
Missouri	N/A

State	Reason for Selecting the Method
Utah	N/A
Ohio	Research
Indiana	On a Trial Basis + Cost
Arkansas	N/A
Minnesota	Cost
Nevada	Cost
Georgia	N/A
Wyoming	On a Trial Basis
Massachusetts	On a Trial Basis + Cost
Montana	On a Trial Basis

Based on the information of Table 3.1, it is evident that only 18% of states have conducted research to overcome the RC on HMA overlays. 41% of the respondents use their past experiences for selecting the mitigation method. 24% consider the cost of the mitigation method before selecting it. This information is showed in Figure 3.2 in another way.

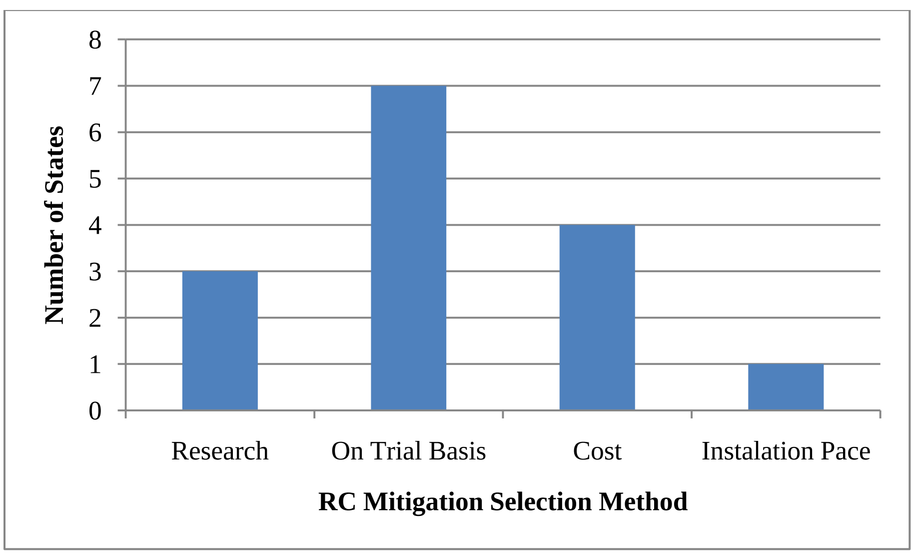
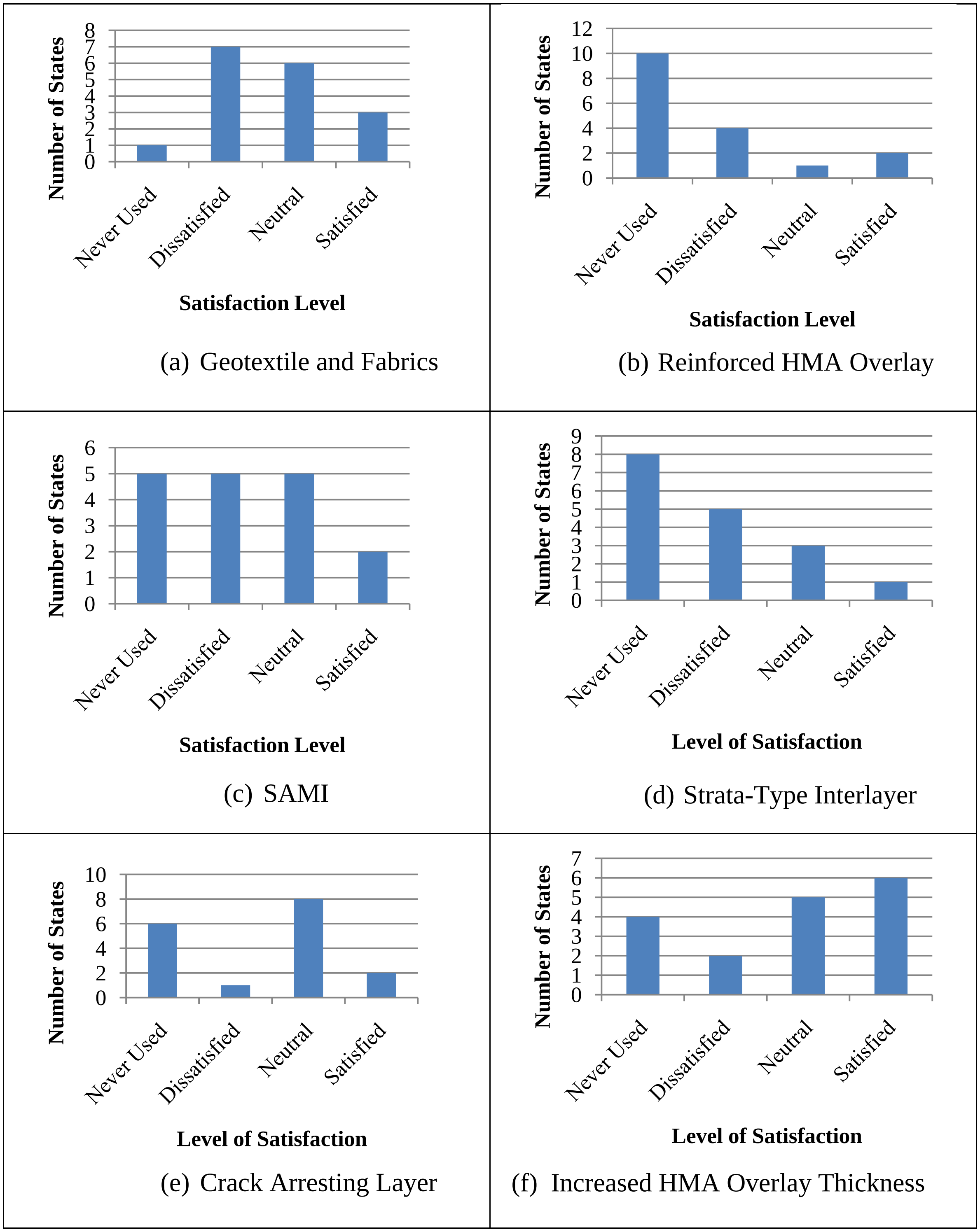


Figure 3. 2 Reason of Selecting Reflective Cracking Mitigation Techniques

1) Paving Fabrics/Geotextiles
2) Reinforced HMA overlay(i.e. geogrids, steel, fiberglass)
3) Stress absorbing membrane interlayer (SAMI)
4) Strata-type inter layer
5) Crack-arresting layer
6) Increase overlay thickness
7) Others

Among the respondents, which mentioned other mitigation methods, Illinois have used Interlayer Stress Absorbing Composite (ISAC) and evaluated its performance as neutral. Iowa have tried Cold-In-Place Recycling (CIR) and Georgia have used crack filling without any comments on its performance. Missouri have used Fiberglass Joint Treatment but did appear unsatisfied performance. Utah have used CIR and mentioned that has neutral performance. Wyoming have used milling and sawing cracks and Massachusetts have used gap graded Asphalt Rubber (AR) .Both of the recent states were satisfied with the performance of the utilized methods.



(a) Geotextile and Fabrics
(b) Reinforced HMA Overlay
(c) SAMI
(d) Strata-Type Interlayer
(e) Crack Arresting Layer
(f) Increased HMA Overlay Thickness

Figure 3. 3 RC Method of Treatment and Satisfaction Level

Figure 3.4 shows the map of responded states and their expectation from the employed mitigation method. Considering this map, it is evident that most of southern states which could be a better peer state in term of climate resemblance have not responded to the survey. Moreover, no trend could be found between level of performance expectation and geographical location of state.

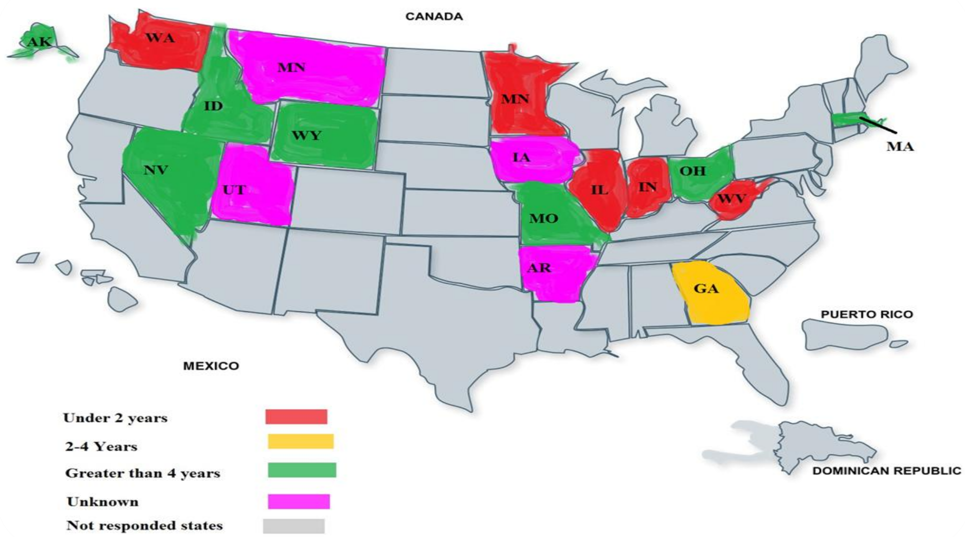


Figure 3. 4 Expectation from the Mitigation Methods to Last Prior to RC Observation

Respondents were asked about the criteria they are using to determine the appropriate RC mitigation method. 100% of the state highway agencies perform visual condition survey as an evaluation means of the existing condition of pavements prior to the overlay placement and as an input for selecting the RC mitigation method. Figure 3.5 shows the key input factors to be considered from each DOT.

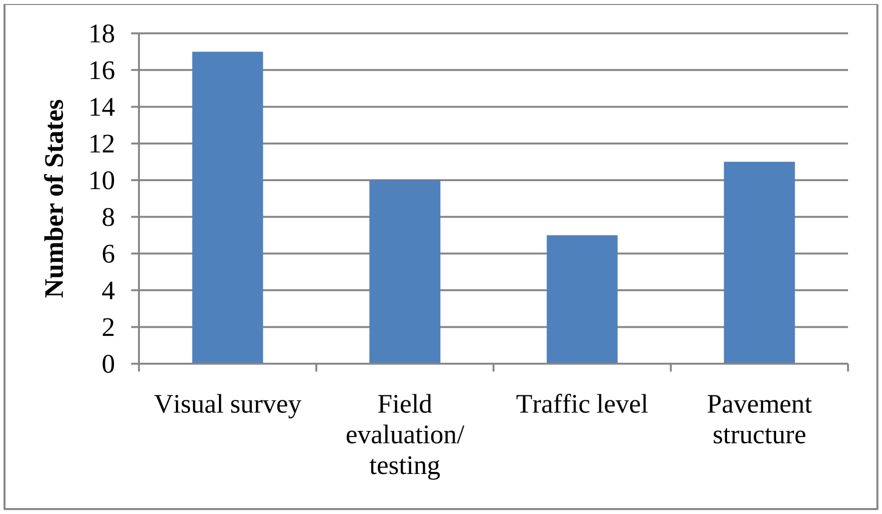


Figure 3. 5 Key Input Factors to be Considered for Selecting the RC Mitigation Method

The thickness of the HMA overlay is one of the key parameters for the success of a mitigation method. Respondents were asked about the typical overlay thickness in their states. The typical thicknesses were classified in 1 inch intervals and being presented in Figure 3.6. As shown in the figure, overlay thickness of 1 inch to 2 inches is the most typical thickness which is being placed over the mitigation methods (46%). As discussed in Chapter 2 of this study, Carmichael and Amini (Carmichael, 1999; Amini, 2005) reported that insufficient overlay thickness likely causes premature failure.

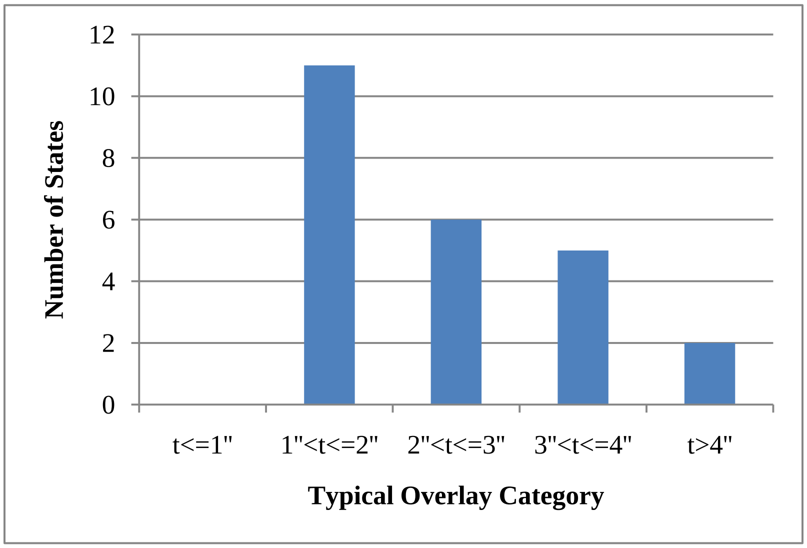


Figure 3. 6 Typical Overlay thickness over RC mitigation methods (t=HMA overlay thickness)

The most successful method for the RC mitigation varies with each state. Among them, 6 states mentioned that increasing overlay thickness worked better than other methods in retarding RC distresses. The next successful method was crack arresting layer (referred as stress/strain relief interlayer). Figure 3.7 shows the number of states that answered the most successful RC mitigation method based on their field studies. Among the states selecting “other”, Utah stated that CIR worked better than other methods. Arkansas did not choose any method and they have utilized all the RC methods and marked dissatisfaction for their performance. Massachusetts mentioned that milling the old pavement and implementing SAMI overlaid with thick HMA has been the most successful method in that state.

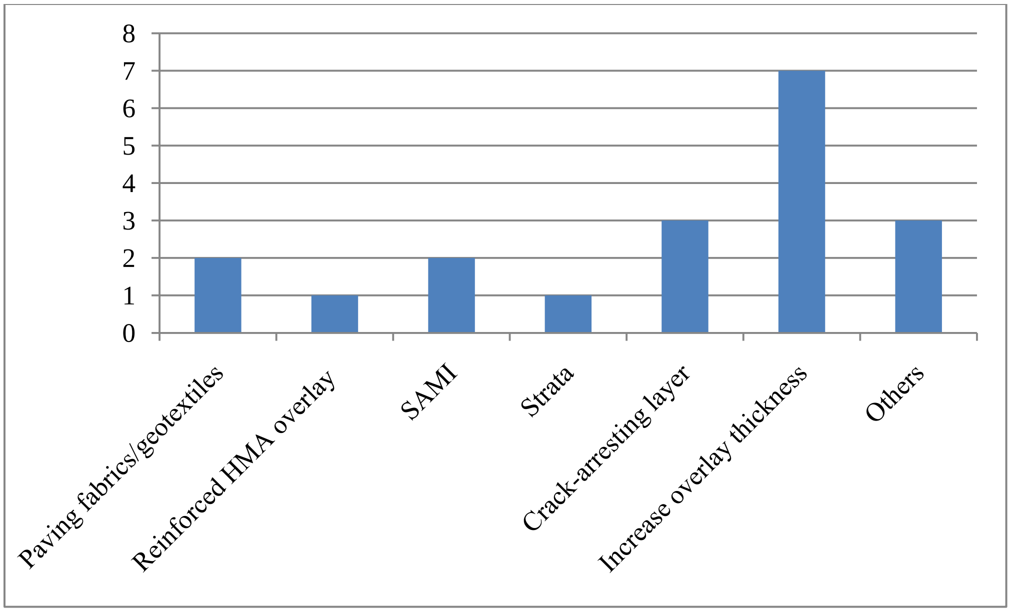


Figure 3. 7 The Most Successful method of RC Mitigation in each State

To enhance the success of a particular RC mitigation method, an evaluation of the existing pavement is essential. The survey questionnaire includes how to evaluate the existing pavement condition prior to designing the HMA overlay for a flexible pavement. All of the respondents mentioned that at least they conduct visual condition survey to identify the surface distresses on the existing pavements. Most of them are using more than one method of pavement evaluation. Figure 3.8 demonstrates the number of states that specific evaluation methods. Among the respondents, Utah and Minnesota mentioned that they utilize lab testing for the pavement evaluation. Minnesota provided additional information that they employ Pave Tech Van for recording pavement profile, rutting and faulting.

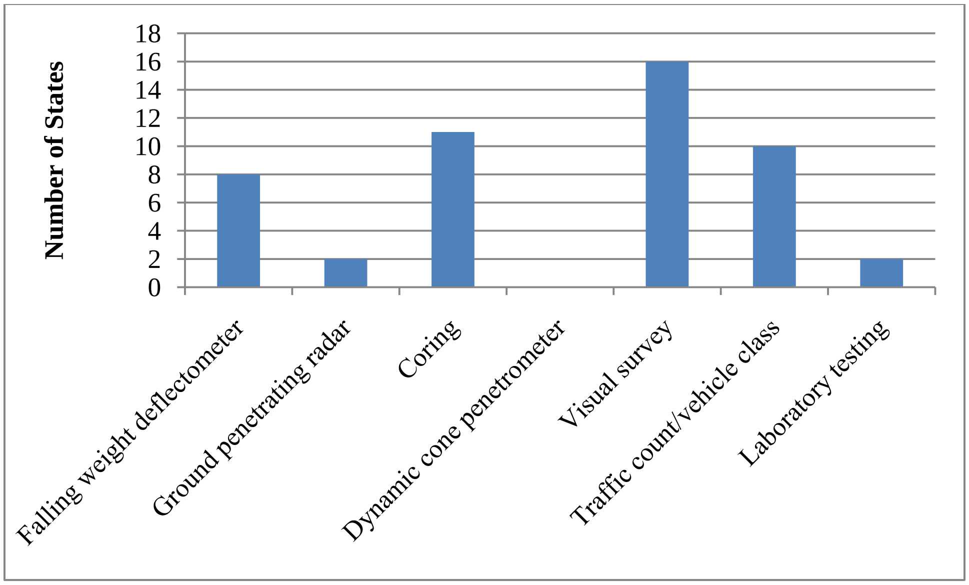


Figure 3. 8 Pavement Tests and Measurements Prior to Designing the HMA Overlay

The respondents were also asked about any typical rehabilitation treatments on the existing flexible pavement prior to placing the HMA overlay. Figure 3.9 shows the number of states which are applying treatments on old pavements. In this figure, the specific treatments as examples in the survey are: 1) Surface repairs (e.g., crack sealing, patching, etc.), 2) Milling only, 3) Milling and replace wearing surface (or inlay), 4) Hot-in place recycling and heater scarification, 5) Full-depth reclamation, and 6) No treatment.

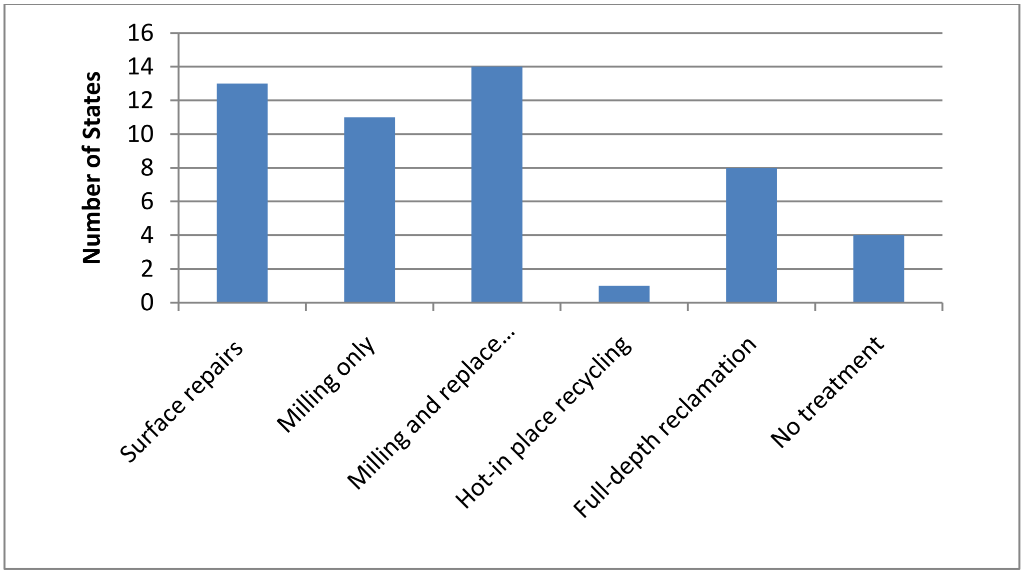


Figure 3. 9 Typical Treatment Used to Prepare the Old Pavement Prior to HMA Overlay

Five states indicated that they use treatments other than aforementioned ones. Iowa mentioned that they usually use CIR, surface repairs and milling treatments. Utah uses CIR along with milling. Ohio State not only utilizes milling method on old pavements, but also they use partial or full depth repairs depending on need. Minnesota and Montana mentioned CIR as one of the treatment they typically do before placing HMA overlay.

Each state DOT designs the HMA overlay using either an overlay design guideline or simply uses minimum thickness. Most of states (13 out of 17) are using design guidelines including AASHTO, Asphalt Institute, DARWin, Mechanistic-Empirical Pavement Design Guide (MEPDG), WINFLEX program developed by University of Idaho and Shell method based on California Bearing Ratio (CBR). Figure 3.10 shows the percentage of the states for the overlay design method.

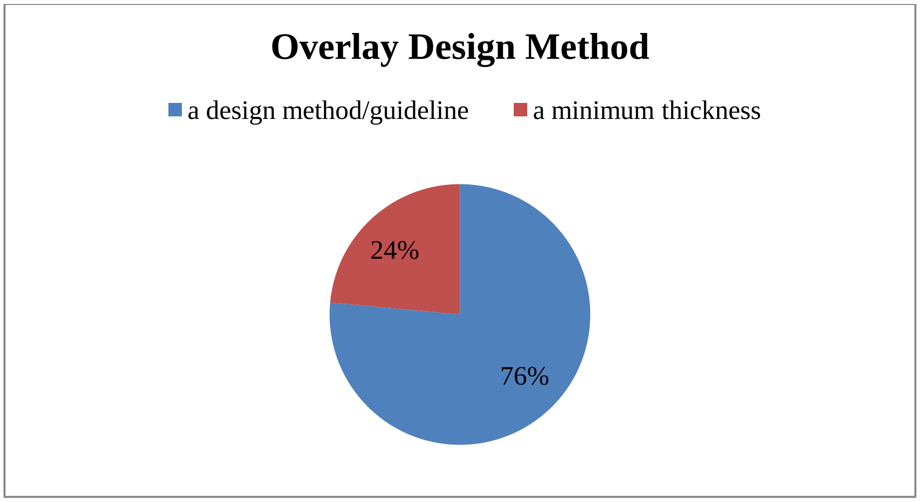


Figure 3. 10 Overlay Design Methods

Among those who selected minimum thickness for overlay designing, they were asked about the design input parameters for selecting the minimum thickness (see Figure 3.11). States which employ minimum overlay thickness are West Virginia, Washington, Missouri and Montana.

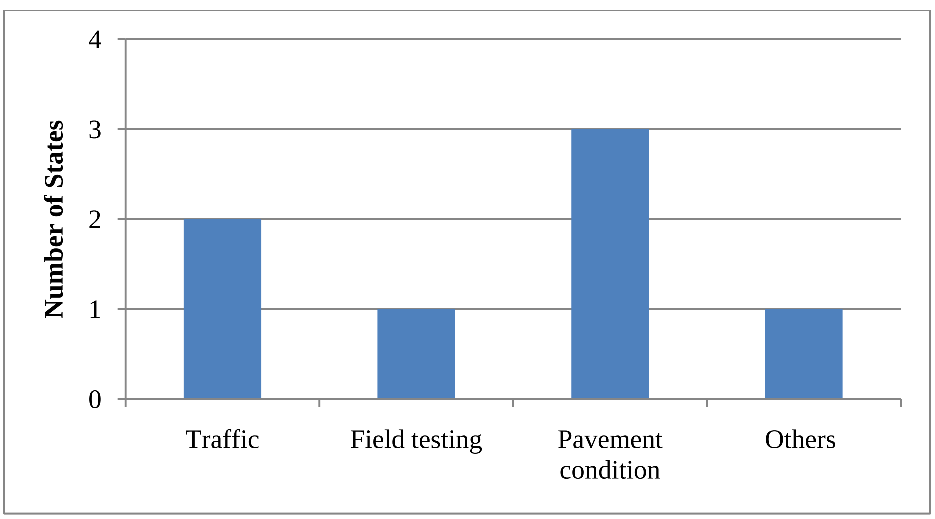


Figure 3. 11 Parameters to be considered for Selecting Minimum Overlay Thickness

When RC mitigation method selection comes to Life Cycle Cost Analysis (LCCA), about 70% of state DOTs are not considering cost analysis. Only 5 states out of 17 fulfill the LCCA for each method of treatment.

Moreover, the respondents were asked if they consider the life cycle cost analysis before selecting the RC mitigation method. Only 29% of states consider this analysis where others (71%) do not consider it.

To get information for cost analysis purpose (ongoing study), the respondents were asked to provide the unit cost of the mitigation methods which they are using in their states. Detailed responses are presented in section 3.5.

3.6 Survey Result Analysis

In this section some statistical analyses have been conducted on the survey results to better understand them. Considering total seventeen respondents, more responses should be collected for more accurate statistical analysis. This analysis is based on only 17 responses from state DOTs. Survey results indicate that 100% of the respondents have observed RC on HMA overlays. Due to high prevalence of this type of distress over the United Sates, it is very important to find and use RC mitigation method based on each state's special condition. About 88% of the states observe RC within the first 4 years of overlay construction while 50% of these states observed it within the first 2 years. This could be an indication of selecting an inappropriate method of mitigation.

This fact can be observed in Figure 3.2 when comparing the satisfaction level of each method of mitigation. In the case of paving fabrics or geotextile, 81% of the states which used it were not satisfied with its performance in retarding the RC on HMA overlays. This percentage is 71% for reinforced HMA overlay, 83% for SAMI, 89% for Strata, 82% for Crack Arresting Layer and 54% for Thick HMA. Among all the methods, placing thick HMA overlay was the most successful one and reinforcing the overlay with geogrid, steel or fiberglass is in the second place. However, comparing to geotextile (which is the third successful method) reinforcing the overlay has less being used.

In terms of the using a criteria for selecting an appropriate method of RC mitigation, all of the states answered that they use at least visual condition survey to evaluate the existing condition of pavements so that an appropriate RC mitigation method is selected. West Virginia, Washington and Alaska are the states that only visually inspect the old pavement.

Most of the states include both visual condition survey and field coring for more details about the existing pavement. More pavement tests and further evaluations such as Falling Weight Deflectometer (FWD), Dynamic Cone Penetration (DCP), and Ground Penetrating Radar (GPR) are recommended.

After the pavement evaluation but prior to the overlay, appropriate rehabilitation treatments are essential to remove the existing distress. Milling and replacing the old pavement (82% of the states) and surface treatment including crack sealing and patching (76% of states) are common methods in the United States.

In addition, about 70% of the states are not considering LCC analysis for selecting the RC mitigation method. It is important to know the cost and benefit of each method to prevent highway agencies from not selecting an appropriate method only due to its initial cost.

Lastly, cost analysis is one of the most important parameters in the engineering area. More than 70% of states are not economically analyzing the method of mitigation prior to selecting it. Cost analysis could better provide the future insight of the utilized method which enables them select the most appropriate method.

3.7 Conclusion

A nationwide survey was conducted to investigate the current practices of RC mitigation management and understand the effectiveness of them in different states. Based on the survey results, RC distresses are prevalent in the United States; however, the level of success in treating it is not satisfactory. The survey results indicate that increasing the overlay thickness is the most promising method but the combination of RC mitigation techniques such as crack arresting interlayer or overlay reinforcement may cause more sustainable long-term performance. All things considered, although RC distresses are widespread in the United States, more study is needed to overcome or retard its initiation on HMA overlays. The best method of mitigation would be different based on geographical location and climate.

The development of a strategy to properly mitigate reflective cracking is discussed in next chapters.

CHAPTER 4: POTENTIAL REFLECTIVE CRACKING MITIGATION METHOD SELECTION

4.1 Introduction

One of the main goals of this study is selecting the optimum method of RC mitigation for both flexible and rigid pavements. This chapter raises the concept of key parameters in RC mitigation performance and discusses about Florida's special conditions. Later in this chapter the RC mitigation method will be introduced.

4.2 General Concepts

The nationwide survey results show that most of the state departments select the mitigation method based on their past experiences. If the selected RC mitigation method worked as expected based on the past experience and during years, the method will remain in use. If not, research could help to select a better method. Pavement condition assessment includes pavement's structural condition, climate and traffic level. In Chapter 2, three main possible mechanisms of RC cracking were discussed. Based on the discussion, these three mechanisms can be categorized as below:

1) Crack initiation under load traffic

2) Crack initiation under thermal load

3) Crack initiation due to PCC curling

Reflective cracks are usually formed by combinations of these three mechanisms. Therefore, condition assessment of the existing road is necessary before selecting an appropriate RC mitigation method. This road evaluation includes:

1) Evaluation of structural capacity of the existing pavement

2) Distress evaluation

3) Traffic

4) Climate condition

Based on AASHTO flexible pavement structural design, an exact evaluation of traffic volume can be used in overlay design (AASHTO, 1993). The overlay thickness should be selected using traffic volume and Resilient Modulus ($\mathbf{M_r}$) of pavement subgrade soil. According to literature, there were less success for the mitigation methods overlaid with thin HMA (Carmichael, 1999; Amini, 2005). Thus, HMA overlay not only functions as a layer to distribute the traffic stresses, but also is a protection for the RC mitigation method.

On the other hand, climate condition, including daily temperature change, high temperature and rainfall, can highly affect the performance of the RC mitigation methods. In a study it was concluded that paving fabrics perform better in hot and mild locations compared to cold ones (Amini, 2005). Climate condition evaluation can truly impact on the result of the mitigation method.

4.3 Key Parameters on Reflective Cracking Performance

After reviewing several publications and DOT reports, it was concluded that there are five main factors that influence the performance of RC mitigation methods. These factors are: 1) overlay thickness, 2) existing pavement condition, 3) base/subgrade support condition, 4) environmental condition and 5) traffic level.

4.3.1 Overlay Thickness

A Texas study demonstrates the effect of overlay thickness and a combination of several other studies by investigating the overlay thickness effect and its performance. The effect of the paving fabric within pavements is shown in Figure 4.1.

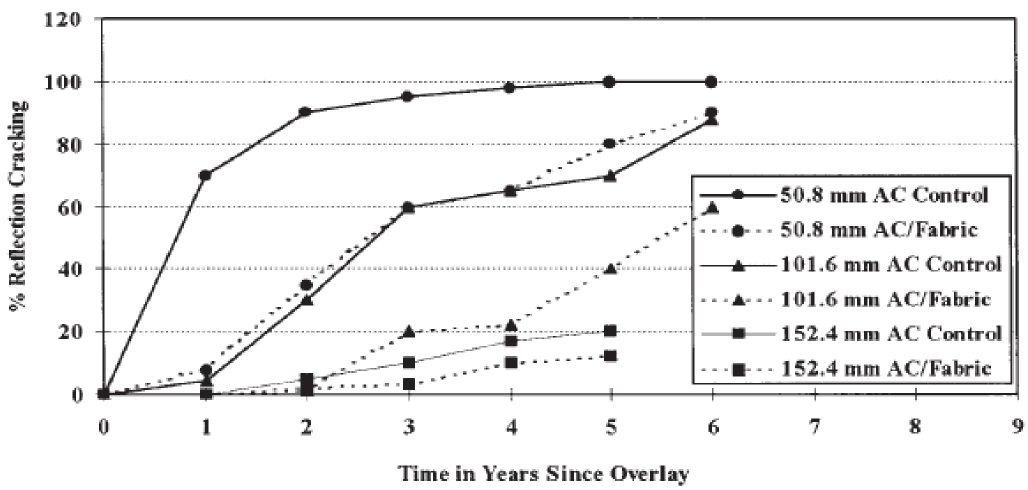


Figure 4. 1 Reflective Cracking over Time for Sections Having Different Overlay Thickness (Carmichael and Marienfeld, 1999).

4.3.2 Existing Pavement Condition

While designing the rehabilitation with overlay with fabric, the extent and severity of cracking as well as other existing distresses in the ACC pavement should be quantified and examined. The existing cracks should be repaired with filling and sealing before the placement of the paving fabric. This allows for a uniform surface for the tack coat to result in a smooth surface for the fabric to adhere to. In some situations with minimal width of cracks, filling may not be necessary as the fabric can be expected to bridge over theses thin cracks, but larger width cracks (greater than 6.4 mm (0.25 in.)) would require the repair of existing cracks.

4.3.3 Base/Subgrade Support Condition

Before starting a rehabilitation project to include paving fabric it may be necessary to inspect the existing base or subgrade support conditions. This can be done either by visual inspection of the site or more accurately by deflection studies to determine if an upgrade is needed. Deflection studies are helpful to differentiate between poor subgrade support, fatigue, and disintegration of the pavement structure. The paving fabric can be helpful to control moisture in the subgrade and therefore improve the overall health of the pavement, but fabric does not necessarily contribute to the structural capacity. Studies have shown that including a paving fabric can delay the start of reflective cracking for about 1.5 years. However it should be noted that the use of the fabric alone should not be expected to resolve existing structural inadequacies.

4.3.4 Environmental Factor

The most important environmental effect to be considered is the temperature conditions. In severe cold climates, freezing and thawing of the pavement causes contractions and expansions within the pavement. The infiltrated water results in excessive damages to the pavement system specially after a cycle of freeze and thaw. The performance of fabric varies largely between warm and cold climates. During the onset of a hard winter, pavements can develop up to 90% of thermal cracking, which in fact, has been occurred in the overlay and has not reflected from the bottom to the top. In warmer climates the use of the fabric performs much better and results in satisfactory reduction of reflective cracking with the minimum overlay thickness of 2 in. Figure 4.2 shows the typical time until reflective cracking is observed in the HMA overlay.

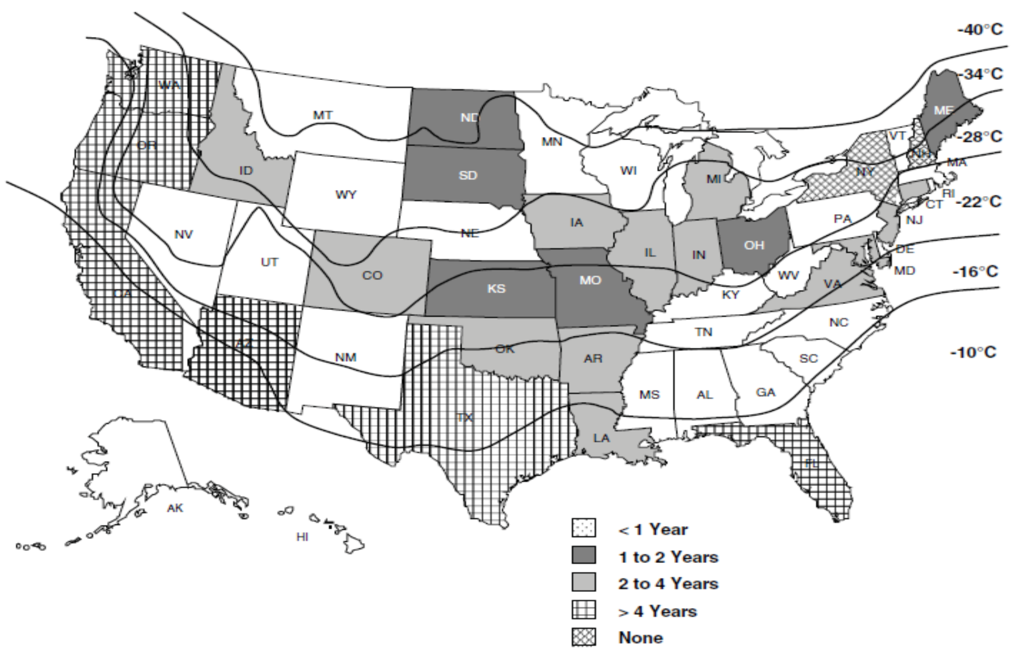


Figure 4. 2 Time to Observe Reflective Cracking after Placing the HMA Overlay (Bennert & Maher, 2007).

4.3.1 Traffic Level

Bennert and Maher (2007) conducted a survey on state highway agencies asking typical traffic levels (ESALs) where reflective cracking on composite pavements (HMA overlay over PCC) has been problematic. The ranges of ESALs asked in the survey were 1) < 3 million, 2) 3 to 30 million, and 3) > 30 million. Most agencies respond to 3-30 million ESALs (58%), and 39% responded to greater than 30 million and the remaining 3% responded to less than 3 million ESALs. The results show that reflective cracking is observed on composite pavements having 3 to 30 million ESALs. It is important note that not many PCC pavements are constructed for low traffic-volume roads (e.g., farm-to-market roads).

4.4 Florida's Special Condition

4.4.1 Top-Down Cracking

As one of the Florida's special conditions, in flexible pavements, the most common distress modes are rutting and top-down cracking (Sholar & Moseley, 2006). Potential mechanism and parameters of top-down cracking have been identified as followings (Birgisson, Wang and Roque, 2004).

1) Transverse contact stresses induced by radial truck tires.
2) Thermal stresses induced by cooling.
3) Age-hardening, which is greatest near the surface of the HMA layer, resulting in greater stiffness (higher stresses) and embrittlement (lower resistance to fracture).

To overcome this type of cracks, use of polymer modified asphalt binder (PMA) in HMA overlay mixture could be proposed. Polymer modified asphalt binder improves the rutting performance by increasing the asphalt binder stiffness and effectively increasing the recovering function of the mixture after loading (high loading cycle life) and meanwhile, increasing flexural strength of it. Polymers contribute to higher stiffness with no reduction in flexibility in asphalt mixtures (Gayle & Helen, 1988). Moreover, It has been proven that using polymer modified asphalt binder in low interconnected air voids asphalt mixture decreases binder hardening due to aging (Woo et al., 2007).

4.4.2 Climate

In a study, average monthly minimum and maximum temperature of seven FDOT Districts have been investigated by finding the temperatures of two cities in each District. Results are shown in Table 4.1 and 4.2 for the maximum (during summer) and minimum (during winter) temperatures, respectively. Figure 4.3 shows the FDOT Districts and Counties. Data were obtained from Southeast Regional Climate Center, the University of North Carolina website (Southeast Regional Climate Center). Table 4.3 shows mean value and standard deviation of minimum and maximum temperatures.

Table 4. 1 Average Maximum Air Temperature During Summer in Florida

(Data Source: Southeast Regional Climate Center)

FDOT District	City	Average Max in Summer, ^{o}F				Period of Record
		Jun	Jul	Aug	Mean	
District 1	Lakeland	90.6	91.7	91.4	91.2	7/ 1/1948 to 8/31/1995
	Naples	90.1	91.4	91.8	91.1	3/ 1/1942 to 4/30/2012
District 2	Madison	90.9	91.3	91.2	91.1	1/ 1/1892 to 4/30/2012
	Cross City	90.2	90.7	90.6	90.5	7/ 1/1948 to 4/30/2012
District 3	Pensacola	89.1	90.2	90	89.8	7/ 1/1948 to 4/30/2012
	Apalachicola	87.6	88.9	88.7	88.4	3/ 1/1931 to 4/30/2012
District 4	Vero Beach	88.4	89.8	89.9	89.4	12/1/1923 to 4/30/2012
	Fort Lauderdale	88.4	89.9	90.5	89.6	11/1/1912 to 4/30/2012
District 5	Orlando	90.8	91.8	91.6	91.4	2/ 1/1974 to 4/30/2012
	Ocala	91.3	91.8	91.8	91.6	1/ 1/1892 to 4/30/2012
District 6	Key West	88	89.4	89.7	89	7/ 1/1948 to 4/30/2012
	Miami	88.3	89.6	89.9	89.3	7/ 1/1948 to 4/30/2012
District 7	Inverness	90.6	91	91	90.9	2/ 1/1899 to 4/30/2012
	Tampa	89.7	90.1	90.4	90.1	3/25/1900 to 4/30/2012

Table 4. 2 Average Minimum Air Temperature during Winter in Florida

(Data Source: Southeast Regional Climate Center)

FDOT District	City	Average Min in Winter, ^{o}F				
		Dec	Jan	Feb	Mean	Period of Record
District 1	Lakeland	52.5	50.7	52.3	51.8	7/ 1/1948 to 8/31/1995
	Naples	56	54.1	55	55.03	3/ 1/1942 to 4/30/2012
District 2	Madison	43.3	42.3	44.5	43.4	1/ 1/1892 to 4/30/2012
	Cross City	41.9	40.2	43	41.7	7/ 1/1948 to 4/30/2012
District 3	Pensacola	44.6	42.9	45.5	44.3	7/ 1/1948 to 4/30/2012
	Apalachicola	47	45.1	47.4	46.5	3/ 1/1931 to 4/30/2012
District 4	Vero Beach	55.4	52.9	54.8	54.4	12/1/1923 to 4/30/2012
	Fort Lauderdale	60.1	58.3	58.7	59	11/1/1912 to 4/30/2012
District 5	Orlando	52.1	48.6	51.5	50.7	2/ 1/1974 to 4/30/2012
	Ocala	47.1	46	47.6	46.9	1/ 1/1892 to 4/30/2012
District 6	Key West	66.7	64.7	65.7	65.7	7/ 1/1948 to 4/30/2012
	Miami	61.9	59.6	61.1	60.9	7/ 1/1948 to 4/30/2012
District 7	Inverness	46.6	45.2	46.7	46.2	2/ 1/1899 to 4/30/2012
	Tampa	52.6	50.9	52.6	52	3/25/1900 to 4/30/2012

Table 4. 3Mean Value and Standard Deviation of Minimum and Maximum Temperatures

	Summer	Winter
Mean, ^{o}F	90.2	1.3
Standard Deviation, ^{o}F	1.0	7.1

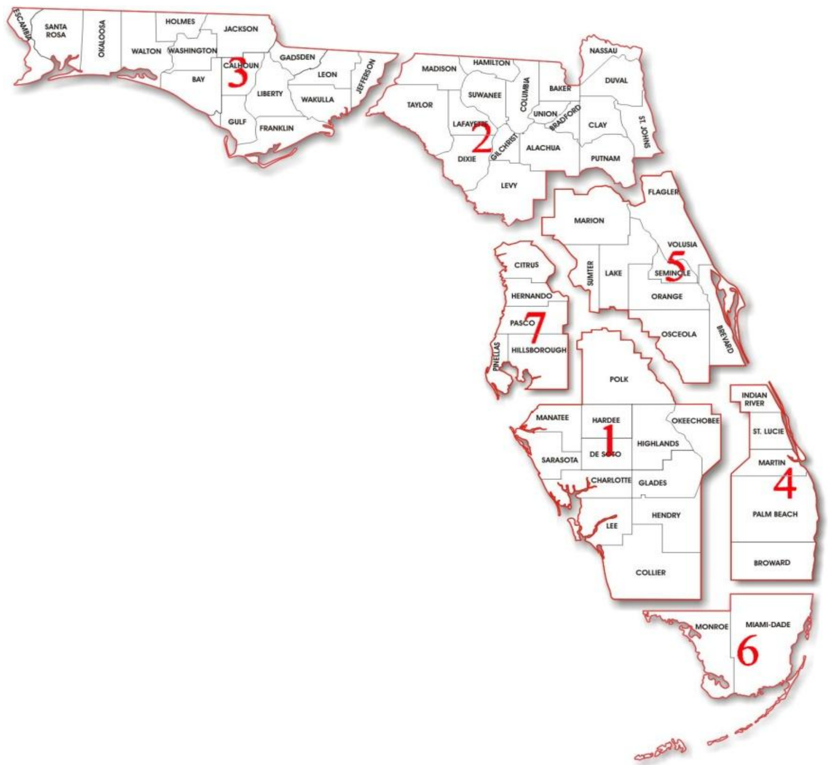


Figure 4. 3 FDOT Districts' Borders (FDOT website)

4.5 Selecting of optimum RC Mitigation Method

Based on the RC mechanisms, it is very important to identify the principal movement type of the underlying pavements at joints and cracks. The first mechanism is initiating RC due to traffic load. Traffic load is being applied vertically and results in vertical differential movements at joints or cracks. This vertical deflection is significant with poor load transfer efficiency (LTE) and in presence of voids underneath the surface layer.

The second mechanism is the horizontal movement of the underlying pavements due to daily temperature changes. This horizontal movement results in tensile stress and strain at the bottom of HMA overlays. Thus, the RC mitigation method should dissipate the tensile stress or prevent the overlay from large tensile strains.

The last RC mechanism is predominant in PCC pavements. PCC curling occurs at the joints due to temperature gradient (or differential). In PCC curling upward, the underlying PCC slabs would push the overlay upward, and develop tensile stress on top of the HMA overlay. Without traffic loads, this mechanism can cause top-down cracking..

In all the mechanisms traffic loading can accelerate the crack propagation (De Bondt, 1997); therefore traffic level should be considered in HMA overlay design to alleviate the severity of RC appearance.

4.5.1 Coefficient of Thermal Expansion

It is important to find out the primary movement type of the existing pavement during loadings (i.e., traffic, thermal and curling). When the existing pavement is under thermal loading horizontal movement occurs in both flexible and rigid pavements. Thus, the extent of horizontal deformation is important for:

1) Estimate the tension stress and strain
2) If the extension exceeds joint width, PCC spalling would occur which can degrade the existing pavement

The extension value of a pavement depends on (Von Quintus, 2009): 1) Magnitude and rate of temperature change, 2) Slab geometry, 3) Gauge length across the joint or crack, and 4) Properties of the resurfacing material or overlay. Using Equation

4.1, the extent of a material can be linearly calculated. This formula can be used to compare the horizontal movement in flexible and rigid pavements.

$$\Delta \boldsymbol{L} = \boldsymbol{L_0} \times \boldsymbol{\alpha} \times \Delta \boldsymbol{T} \quad (4.1)$$

Where;

$\Delta \boldsymbol{L}$ = the extent of horizontal movement

$\boldsymbol{L_0}$ = initial slab length

$\boldsymbol{\alpha}$ = material's Coefficient of Thermal Expansion (CTE)

$\Delta \boldsymbol{T}$ = temperature change

Therefore, it is necessary to compare the CTE for both flexible and rigid pavements to identify which type of pavement has more critical horizontal movement at the same situations.

According to Iowa Department of Transportation Report (Wang, K.; Hu, J.; Ge, 2008), the CTE of concrete slabs is dependent upon aggregate type and water to cement ratio. However, the range of concrete's CTE is from 7.4 to 13 $\times \boldsymbol{10^{-6}}$ /^{o}C. Concrete CTE can be estimated from the CTE of cement paste and aggregate. Neville (Neville, 1996) reported that the CTE of cement paste generally varies from 11 to 20 $\times \boldsymbol{10^{-6}}$/^{o}C, and the CTE of concrete decreases with the increase of aggregate content (see Table 4.4).

On the other hand, Littlefield (Littlefield, 1967) investigated if different asphalt cements have different CTE when they are heated at temperature between 0^{o}F and 130^{o}F. In another study, CTE of asphalt concrete reported at the range of 25 to 100$\times \boldsymbol{10^{-6}}$/^{o}C (Nesnus and Nunn, 2004).

Therefore, the CTE for flexible pavement is much higher than that of rigid pavement. It can be concluded that at the same situation, flexible pavements have higher extent of horizontal movement due to temperature change.

Table 4. 4 Influence of Aggregate Content on CTE (Neville, 1996)

Cement : Sand Ratio	**CTE (/°C)**
1:0 (Paste)	18.5
1:1	1.35
1:3	11.2
1:6	10.1

4.5.1 PCC Pavement and its Dominant Movements

An HMA overlay placed on rigid pavements is governed by the magnitude of shear and tensile strain in the overlays. Thus, the magnitude of shear and tensile stress should be dissipated using an Interlayer system. Figure 4.4(a) shows the shear stress in HMA overlays due to wheel loading.

The principal shear stress and strain is based on the Equation 4.2.

$$\tau = \gamma G \tag{4.2}$$

Where;

τ = shear stress

γ = shear strain

G = shear modulus (stiffness)

Considering equation 4.2, to dissipate the shear stress due to large shear strain, the low shear modulus layer is required. Since a HMA overlay is required to bear shear stresses and be resistant to permanent deformation, the low stiffness with high flexible material should be placed under the overlay as an interlayer. The low stiffness layer should be stiff enough not to result in permanent deformation by recovering the deformation.

Another RC mechanism is PCC curling under thermal loadings. PCC slab curling results in inflation on HMA overlay (Figure 4.4(b)).

Because of upward movement of slab tips in this mechanism, tension stress on HMA overlay becomes dominant and cracks start to be initiated on the top of the overlay. To prevent or reduce tensile stress on the overlay's surface, slab tips should be controlled while curling upward using strain dissipating material (low stiffness material).

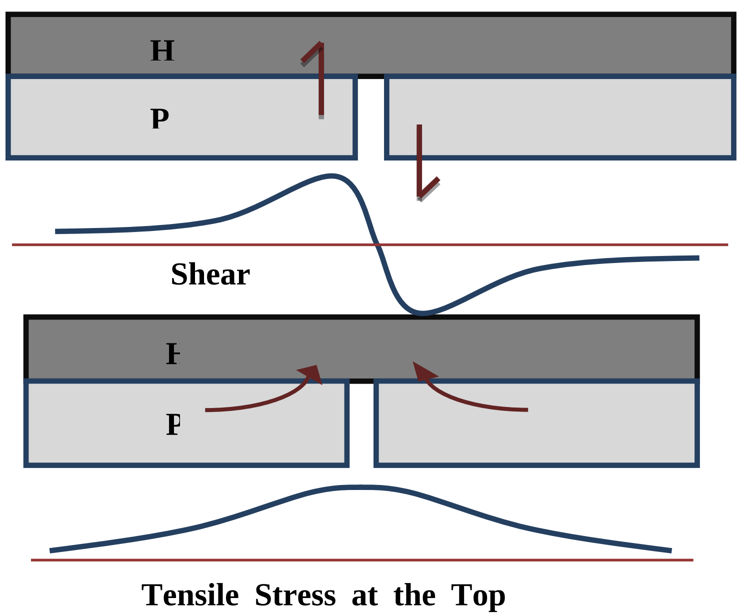


Figure 4. 4 PCC Slab movements due to (a) Differential Vertical Movement and (b) Curling Due to Thermal Changes

4.5.2 Selection of an Optimum RC Mitigation Method

Through the extensive literature studies and personal meetings and interviews with FDOT pavement engineers, clear understanding could be made in the areas of 1) reflective cracking mechanism, 2) practical reflective cracking mitigation methods, 3) reflective cracking affecting parameters, 4) cost-benefit studies on RC mitigation methods, and 4) FDOT practices on the RC mitigation. Findings are summarized below.

In flexible pavements when compared to rigid slabs, horizontal movements in the underlying HMA due to temperature variations changes is more significant. The coefficient of thermal expansion (CTE) of HMA is twice as CTE of PCC (CTE_{HMA} = 25 - 100 micro strain/^{0}C, CTE_{PCC} = 5 – 12 microstrain/^{0}C).

- In HMA overlays over flexible pavements following points should be considered:
- Many researchers believe that traffic loadings are not significant in initiating reflective cracking, but they will accelerate the deterioration (De Bondt, 1998).
- Aging of asphalt mixture can accelerate the damage on the overlay mixture. This mechanism can be explained in Figure 5. As shown in the figure, reflective cracking appear around 3 years after the overlay placement regardless of the mitigation techniques. It is believed that aging of the overlay mixture causes stiffer materials and more susceptibility to thermally induced cracking.

- Carmichael and Marienfeld (1999) have collected information on about 30 sites to study the application of paving fabrics (geotextiles) in the rehabilitation of exiting HMA pavements. Almost all of these case studies (26 out of 30) indicated that the application of paving fabric treatment in the rehabilitation of pavements resulted in reduction in reflective cracking.
- Long-term monitoring illustrates that paving fabrics are effective in reducing reflective cracking in the HMA overlay over flexible pavements but are not effective for the overlay over PCC. It is noted that sufficient thickness of the overlay (e.g., greater than 1.5 in.) should be required. The moisture-control function of fabrics (e.g., waterproofing) helps minimize the freeze-thaw damage and the fabrics works better in warm climate regions.

In rigid pavements, following points should be considered:

- In HMA overlay over rigid pavements when compared to the overlay over flexible pavements, generally larger vertical differential movements at joints/cracks and also the slab curling due to the fact that temperature differentials are much more significant. However, the lower CTE of PCC causes smaller amount of slab expansion/contraction. In particular, vehicle loading under upward slab curling during early morning can produce significant vertical movements (also tensile stress at the crack tips) at joints, resulting in reflective cracking within a short period of time.

- Several studies have shown that the HMA overlay over PCC slabs appear surface-initiated reflective cracking although no traffic loading was applied (Greene, 2012; Nesnas and Nunn, 2004). This explains the mechanism shown in Figure 4.4(b) due to the slab curling of the underlying PCC slabs.

Many studies have shown that geosynthetic applications to rigid pavements are not effective in retarding reflective cracking (Figure 4.5). On the other hand, several studies have shown that stress-absorbing membrane or cushion layers are effective in retarding reflective cracking. Figure 4.6 is the result of a survey on state highway agencies in the U.S. (Bennert and Maher, 2007).

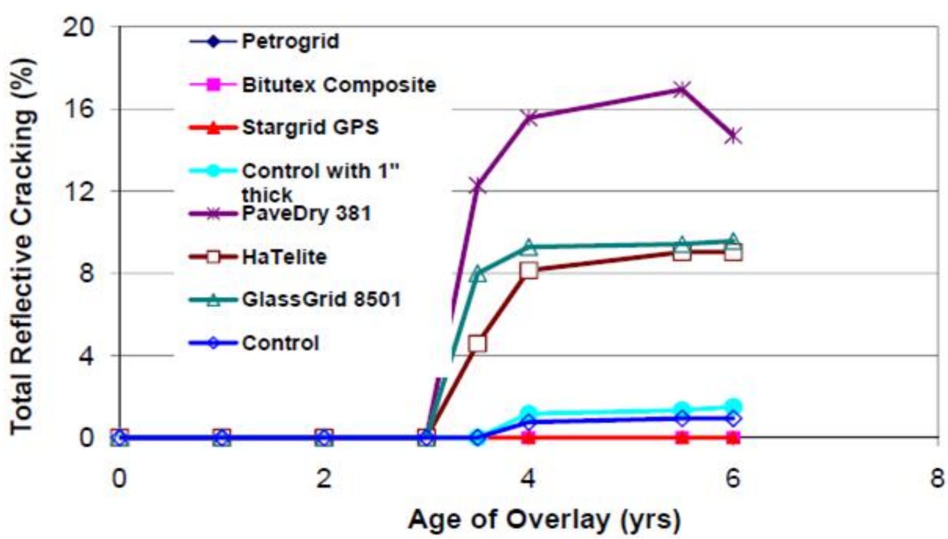


Figure 4. 5 Reflective cracking observation over time for the sections with various mitigation methods (Button and Lytton, 2009).

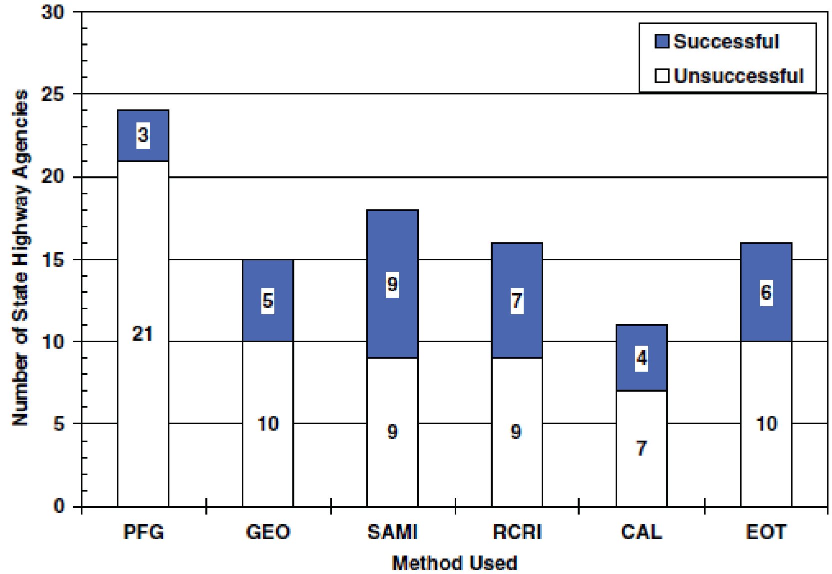


Figure 4.1 Survey results showing the success of different reflective cracking mitigation methods for the overlay over PCC (Bennert and Maher, 2007).

4.6 Conclusion

Based on the findings summarized in this chapter as well as consideration of Florida's special conditions (e.g., material type, distress type, and climate conditions), following tentative conclusions were made.

- Florida's climate is warmer and precipitation is higher than other states. Florida's road consists of 98% asphalt pavement and 2% rigid pavements, and top-down cracking is a major distress type in the asphalt pavements. With severe top-down cracking, if milling depth is not sufficiently deep, milling may not be able to remove all cracks and some portions of top-down cracks will remain.

- In the overlay over asphalt pavements, geosynthetic reinforcements (i.e. geogrid and geocomposite with high tensile strength) can be one of the top solutions to mitigate reflective cracking by resisting the horizontal movement of underlying asphalt pavement. However, if milling cannot remove surface cracking in the existing pavements, stiff crack arresting layer is recommended. Waterproofing and drainage functions of geocomposite may improve the performance of the overlay over flexible pavements. On the other hand, stress-absorbing membrane and cushion layer are soft materials and can lead to excessive permanent deformation.
- In the overlay over PCCs, the stress-relief interlayer system can be one of the top mitigation methods because the interlayer can minimize the stress developed at the joint/crack tips by deforming. The team will continually study the specific types of stress-relief layer and its design parameters such as binder grade, aggregate gradation, additives, thickness, etc.

CHAPTER 5: DECISION TREES FOR REFLECTIVE CRACKING MITIGATION

5.1 Introduction

In the previous chapters, 1) RC mitigation mechanism, 2) currently available RC mitigation methods, 3) RC mitigation management statewide and nationwide and 4) key considerations for selecting proper RC mitigation methods were discussed. The key parameters are: 1) overlay material type and thickness, 2) existing pavement condition, 3) base and subgrade support condition, 4) environmental factors and 5) traffic level. In this chapter, decision trees of RC mitigation method selection are presented. The decision trees were developed for both flexible and rigid pavements.

5.2 Developing Approach of the Decision Tree

A typical approach for the pavement rehabilitation involves 1) condition assessment, 2) site investigation, 3) design input parameters (i.e. environmental and traffic loading), and 4) material type and thickness. The selection of RC mitigation technique would be same as the typical rehabilitation procedure. Figure 5.1 shows the typical thought process of developing the decision tree.

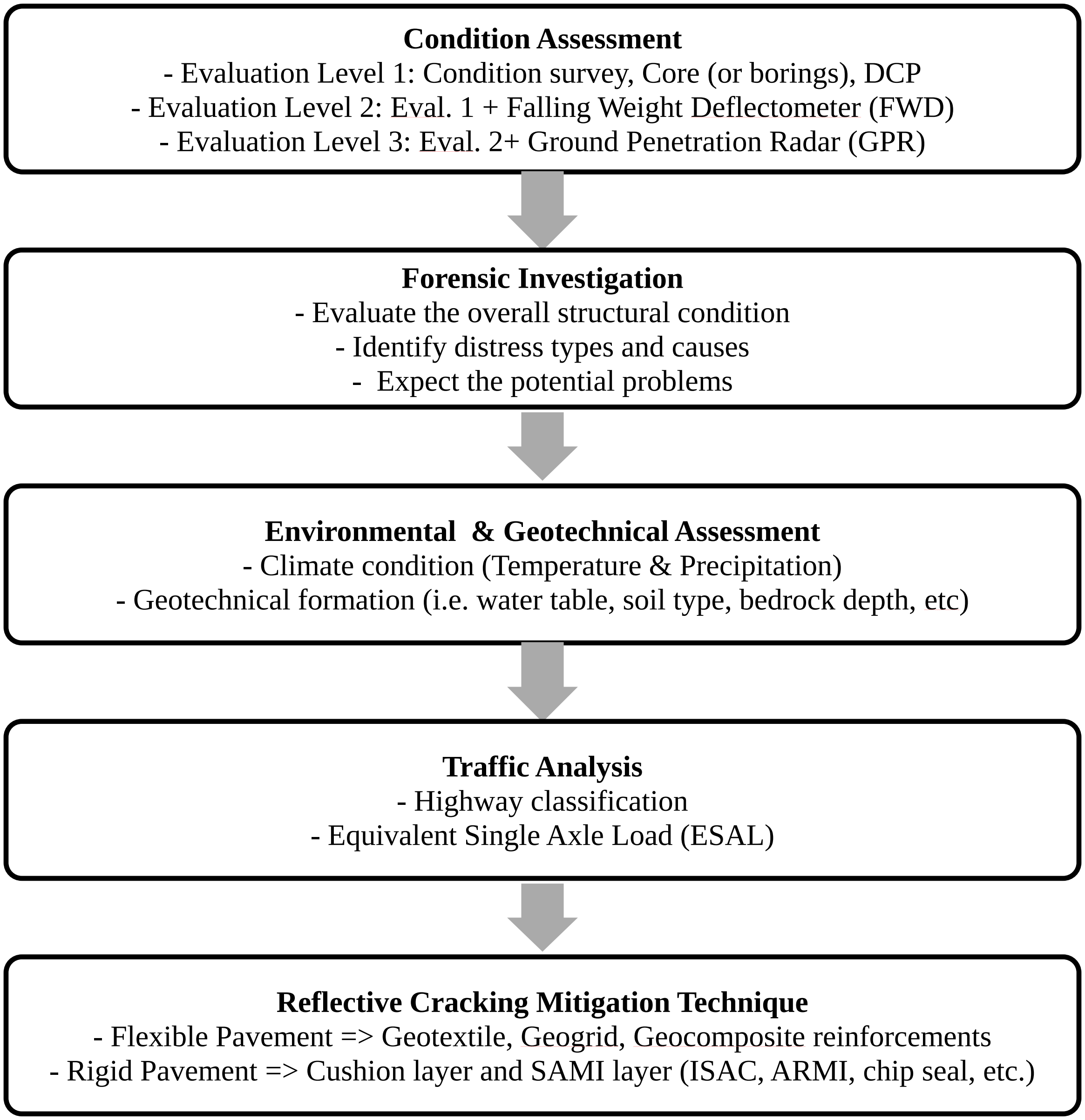


Figure 5. 1 Thinking Process of Developing Decision Trees for RC Mitigation Methods

The purpose of condition assessment is to determine the damage condition and its severity on the existing pavement. Almost all highway agencies employ condition survey but the level of structural condition assessment varies. In particular, nondestructive testing such as FWD and GPR may not be used all the time. Von Quintus et al (2009) addressed that not all highway/airfield agencies will have the funds to complete a full pavement evaluation program. In this study, the level of condition assessment consists of three Evaluation levels as are described:

- **Evaluation 1** (Basic Information of Minimum Data Measurement) – Includes visual condition survey, field coring, and dynamic cone penetrometer (DCP).
- **Evaluation 2** (Pavement Response Measurement) – Includes Evaluation Level 1 with FWD. FWD testing can provide modulus information of pavement layers. In PCC slabs, FWD testing can provide joint load transfer efficiency (LTE).
- **Evaluation 3** (Full Pavement Evaluation Program) – Include Evaluation Level 2 with GPR and other field and laboratory tests for example the measurement of joint closing and opening, and laboratory strength measurement with field cored samples.

Higher level of pavement evaluation will result in more accurate selection of RC mitigation technique and the overlay thickness design.

Pavement forensic investigations, which predict the main cause of pavement distresses, are essential tasks. The main cause of failure should be repaired or removed prior to the placement of new overlays. Structural conditions, distress type and severity will determine the specific RC mitigation technique, the depth of milling, and rehab treatment as well as the overlay thickness design. For instance, for the cracks confined to the wearing surface (shallow-depth cracks) in flexible pavement may require minor surface treatment (i.e. sealing) and shallow depth of milling rather than major rehabilitation such as full-depth repair (FDR) or in-place recycling (IPR). In case when large voids exist underneath the PCC slabs, subsealing, void filling, or rubblizing techniques may be required prior to the overlay placement. Ground water table data can be used as information to evaluate potential of pumping or moisture damage.

After completing the forensic investigation, environmental data and traffic levels should be investigated as design input parameters. For instance, heavy traffic causes large vertical differential movements and high daily temperature change results in large horizontal movements in the underlying pavements. These crack-initiation mechanisms should be taken into account for the selection of the mitigation method.

5.3 Decision Tree

Milling is one of the most widely used rehab treatments in flexible pavements. Thus, three different decision trees were developed; two decision trees are for flexible pavements when optimum rehab treatments or only milling the surface course is used. The third decision three was developed when the existing pavement is rigid. The RC mitigation technique is different for flexible pavements. For all the decision trees, the starting point is evaluating the existing pavement using Evaluation Levels 1, 2 or 3.

Distress types and their severity should be identified at the next step. The traffic level of the road should be determined using traffic evaluation. Finally, the decision should be made based on the evaluated distress type, severity and its traffic level. In a nationwide survey study conducted in New Jersey (Bennert & Maher, 2007), it was found out that about 93% of the RC occurs on roads with traffic level greater than 3 million. Traffic level was consequently divided into two groups:

1) Low Traffic Level: ESAL < 3×10^6

2) High Traffic Level: ESAL > 3×10^6

5.3.1 Decision Tree for Flexible Pavement with Milling Option

In the decision tree shown in Figure 5.2, since a portion of the distresses is being removed by milling process, no further rehabilitation is included in the decision level. For using this decision tree following notes should be considered:

1) Milling depth needs to vary depending on the depth of existing cracks. Some cracks may exist on the surface prior to the new overlay.
2) High traffic requires a stress/strain relieving interlayer but is stiff enough to prevent rutting.
3) Low traffic requires geosynthetics reinforcement (geogrid or geocomposite) because of the increased effect of environmental loading.
4) If drainage is the biggest concern, geotextile or geocomposite should be considered.

5.3.2 Decision Tree for Flexible Pavement with Pre-Overlay Repair Recommendation

In this decision provided in Figure 5.3, no milling option is available; thus reaping the existing pavement has being considered at the decision level of the tree. Therefore, the first level of decision level is repair on the existing pavement. Based on type and extent of the distresses, Full-Depth replacing (FDR), In-Place recycling and milling and replacing wearing course are suggested. The suggested mitigation methods follow the repair options in the decision level. As with the last decision tree, if moisture damage is a big concern, paving fabrics (geotextile) is being considered. This decision tree is shown in figure 5.3.

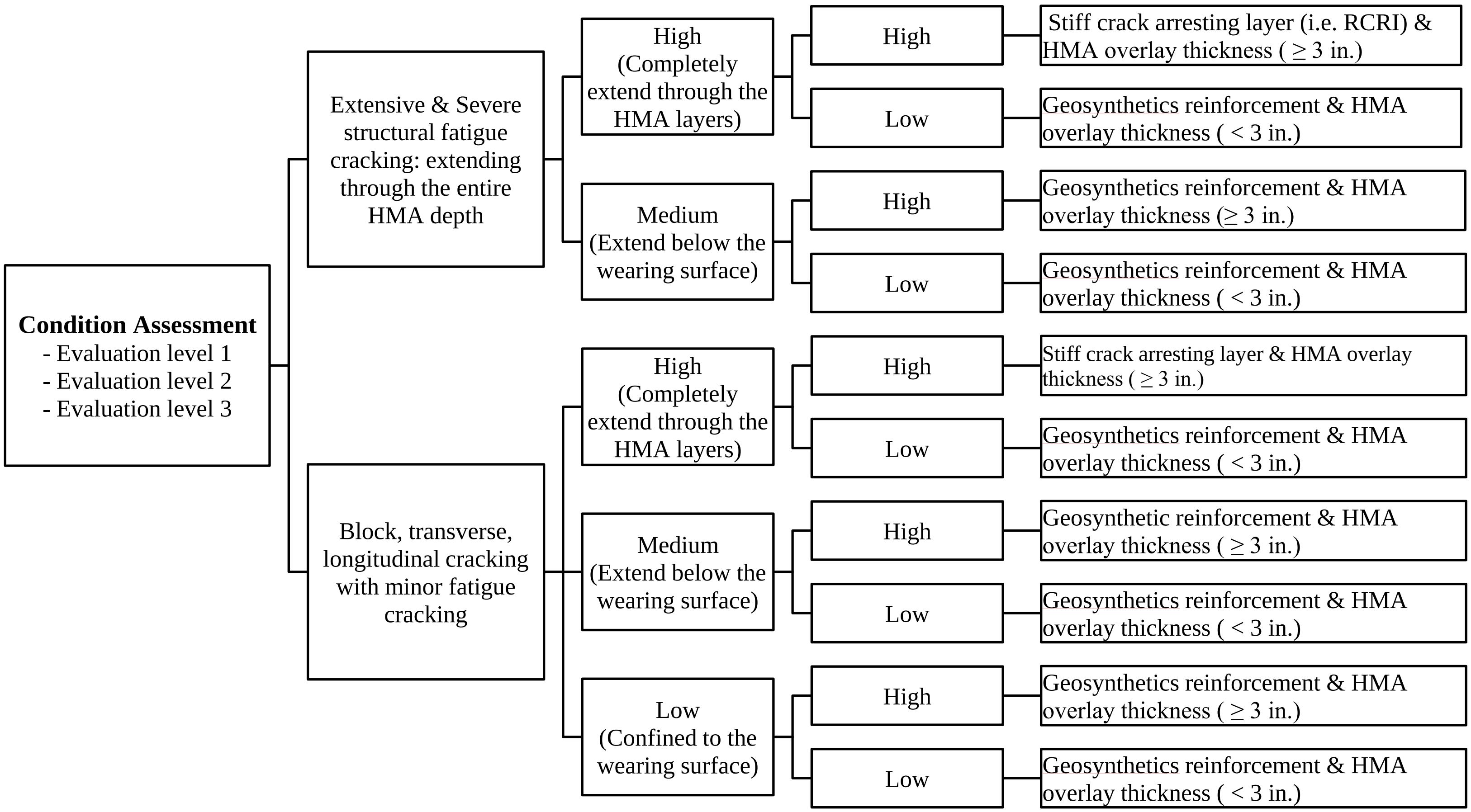


Figure 5. 2 Decision Tree for Flexible Pavement with Milling Option

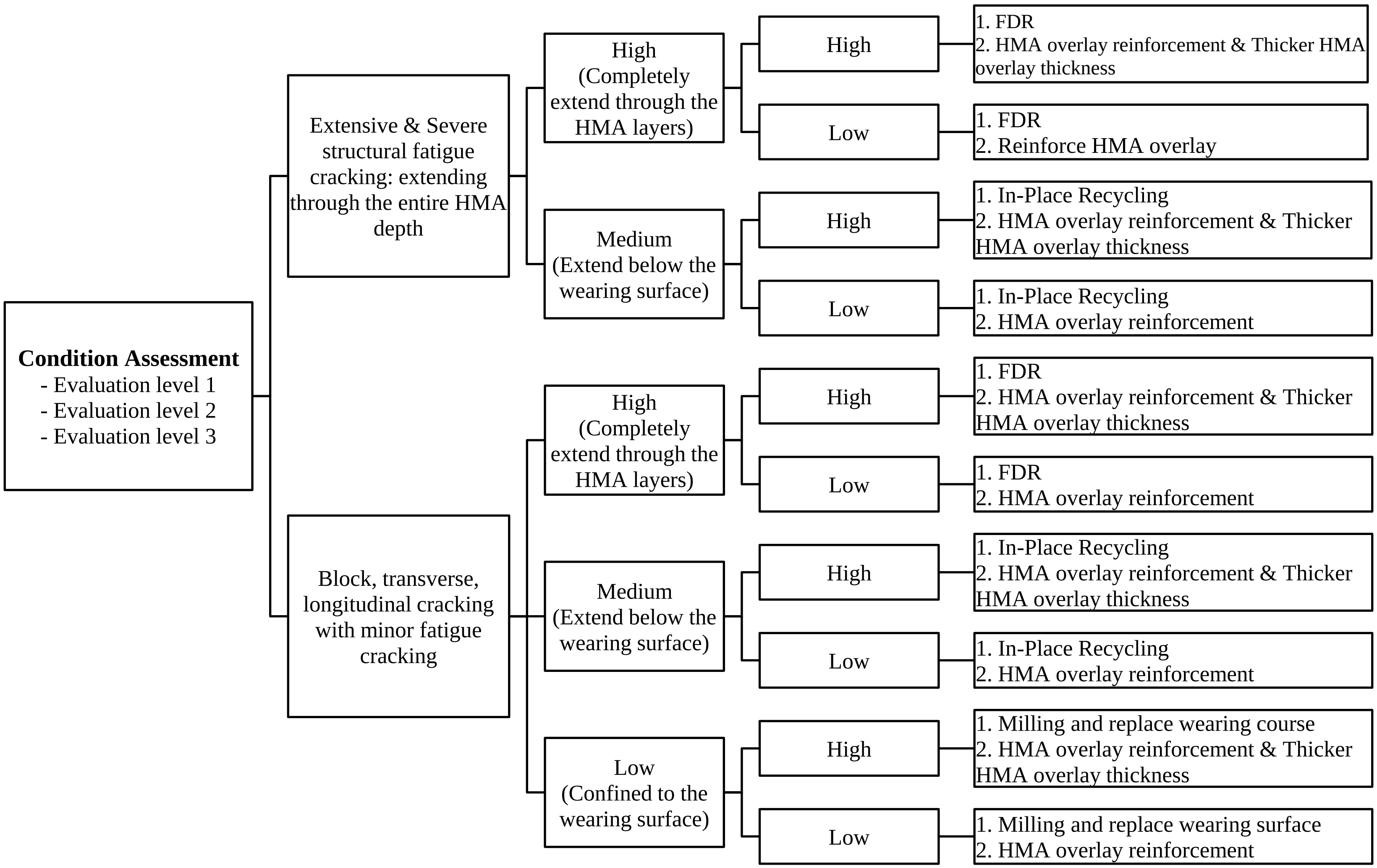


Figure 5. 3 Decision Tree for Flexible Pavement with Pre-Overlay Recommendation

5.3.3 Decision Tree for Rigid Pavements

As like as the developed decision trees for flexible pavement, the decision tree for rigid pavements starts with evaluation of the existing pavement. Distress type and its severity extent of the rigid pavement should be determined based on employing one of the three levels of evaluation presented in this chapter. Employing level three of the evaluation can better help to understand the potential problems of the pavement and considering this level of evaluation depends on the assigned budget for the project.

When distress type and its extension are determined, for severe distresses rubblization of PCC slab is being recommended. Rubblizing can remove the potential problems that exist on old pavement and create a strong and stiff base for the mitigation method and HMA overlay. In the case of moderate extent of distresses, slab fracture (break and seat or crack and seat) should be employed to remove or reduce the problems associated at joints or mid-span cracks. There is no need to repair the slab when severity of distress is low. Following this step, the recommended method should be placed and followed by HMA overlay. It should be considered that in high severity distresses, a thicker mitigation method could be used in order to decrease the stress magnitude.

Before using the decision tree, following notes should be considered:

1) Faulting criteria: Severe = Faulting > 0.15 in.; Minor to Moderate < 0.05 in.
2) Load transfer (LT) criteria: Good LT (> 50mils) or LTE<70%; Moderate LT (10 to 50 mils) or 70<LTE<80%; Good LT (<10 mils), LTE>80%
3) Faulting, Joint max deflection, or LTE can be used for the joint condition.

4) If voids exist under PCC, either Rubblize PCC with no subsealing or filling voids or Fracture PCC with subsealing and filling voids.
5) The decision tree for the rigid pavements is presented in figure 5.4.

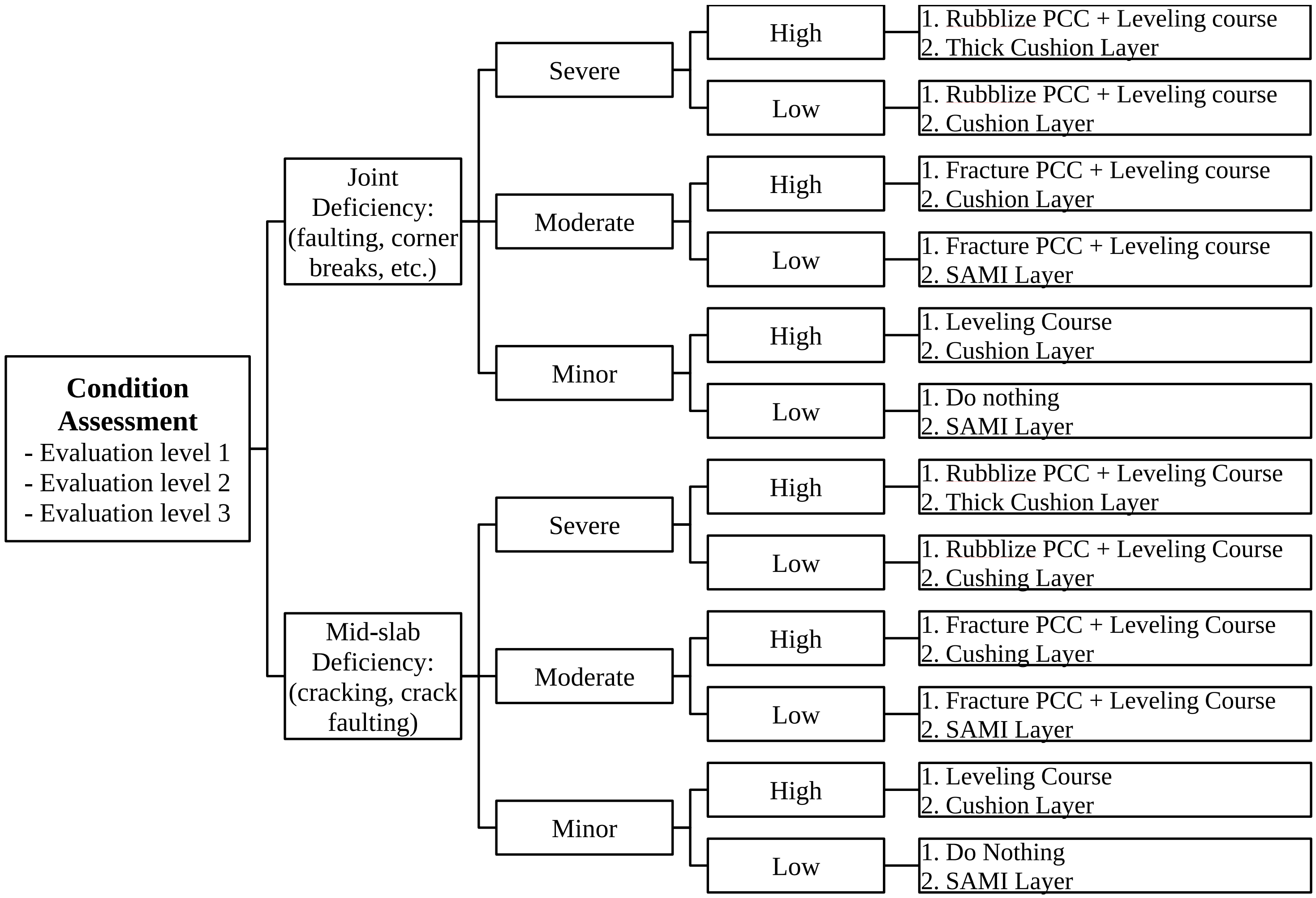


Figure 5. 4 Decision tree for Rigid Pavements

5.4 Conclusion

This chapter presented decision trees to be used as guidelines for pavement engineers. The decision tree should be selected based on the type of pavement and available methods of rehabilitation. For flexible pavements, two rehabilitation options are available before slecting the RC mitigation method. If milling option exists, figure 5.2 should be followed as the decision tree. In the other cases, figure 5.3 would better serve the pavement engineers to rehabilitate and place an appropriate mitigation method on flexible pavements. For rigid pavements, figure 5.4 could be used to address the RC distresses. Rehabilitation methods are available in this guideline.

CHAPTER 6: SUMMARY AND CONCLUSION

6.1 Summary

Reflective cracking can be developed when a HMA overlay is being placed over jointed or severely cracked rigid or flexible pavements. The RC in the HMA overlays can accelerate other pavement distresses such as stripping and weakening sublayer materials (base, subbase, and subgrade) by allowing moisture infiltration. Theretofore, there have been different attempts to prevent or retard the initiation of the RC on HMA overlay over the last two decades.

FDOT has used ARMIs to mitigate RC initiation and propagation in the HMA overlays but the field performance of the ARMI is not always successful. FDOT's APT study showed more rutting in the pavement with the ARMI than the pavement without the ARMI and pavement rutting problems have been observed in several pavement sites with the ARMI (Green, 2012). The main objectives of this study are to understand the current practices of RC management and to identify alternative methods for the RC mitigation in Florida. To achieve the objectives, the followings subtasks have been conducted.

- Conducted extensive literature reviews to understand RC mechanisms and to identify currently available RC mitigation methods. The key design parameters were also investigated through the literature review.

- Conducted a nationwide survey to understand the current practices of RC management at nationwide level. In addition, the current practice of FDOT's RC management has been investigated through personal interviews and publication reviews.
- Developed decision trees for the selection of the best performing RC mitigation method considering Florida's special conditions.

6.2 Findings and Conclusions

The research methodology included literature reviews, personal interviews, and a nationwide survey. Findings of the literature reviews are summarized below.

6.2.1 HMA Overlay over Flexible Pavement

- Compared with PCC slabs, horizontal movements in the underlying HMA due to temperature changes is more significant. The coefficient of thermal expansion (CTE) of HMA is twice as great as the CTE of PCC (CTE_{HMA} = 25 - 100 micro strain/^{0}C, CTE_{PCC} = 5 – 12 microstrain/^{0}C).
- Many researchers believe that traffic loadings are not significant in initiating reflective cracking, but they will accelerate the deterioration (De Bondt, 1998).
- Aging of the overlay mixture causes stiffer materials and more susceptibility to thermally induced cracking.

- Carmichael and Marienfeld (1999) have gathered information on about 30 sites to study the application of paving fabrics (geotextiles) in the rehabilitation of exiting HMA pavements. Almost all of these case studies (26 out of 30) indicated that the application of paving fabric treatment in the rehabilitation of pavements resulted in reduction in reflective cracking.
- Long-term monitoring illustrates that paving fabrics are effective in reducing reflective cracking in the HMA overlay over flexible pavements but are not effective for the overlay over PCC. It is noted that sufficient thickness of the overlay (e.g., greater than 1.5 in.) should be required. The moisture-control function of fabrics also helps minimize the freeze-thaw damage and the fabrics works better in warm climate regions.

6.2.2 HMA Overlay over Rigid Pavements:

- The overlay over PCCs generally involves larger vertical differential movements at joints/cracks due to traffic loading. The combination of traffic and slab curling (due to temperature differential) will cause more significant damage to the overlay than the traffic load only. In particular, vehicle loading under upward slab curling during early morning can produce significant vertical movements (also tensile stress at the crack tips) at joints.
- Compared with HMAs, the coefficient of thermal expansion (CTE) of PCC is smaller, and may cause less slab expansion/contraction. Thus,

PCCs may have smaller horizontal movements due to daily temperature than HMAs.

- Several studies have shown that the HMA overlay over PCC slabs result in surface-initiated reflective cracking (Greene, 2012; Nesnas and Nunn, 2004). Greene (2012) reported reflective cracking on the HMA overlay over PCC slabs are observed although no traffic loading was applied.
- Many literatures have shown that geosynthetic applications to rigid pavements are not effective in retarding reflective cracking. On the other hand, several studies have shown that stress-absorbing membrane or cushion layers are effective in retarding reflective cracking.
- Based on the findings summarized above, the research conclusions were made as below.
- In flexible pavements, the predominant cause of RC may be tensile stress/strain at the bottom of the overlay due to temperature change (horizontal movement due to expansion and contraction) and traffic loading. Therefore, the overlay reinforcement (i.e. geosynthetic reinforcement) can be a proper method to mitigate the RC.
- In rigid pavements, the predominant cause of RC may be the vertical differential movement at joints due to heavy traffic loads. The combination of slab curling, slab contraction, and traffic loads will result in large vertical differential movements at the underlying joints. Thus, a stress absorbing membrane interlayer (SAMI), which is flexible enough to

absorb the differential movements, may be a proper mitigation technique. Depending on the traffic level and structural condition of the underlying slabs, the thickness of SAMI may be increased (called cushion layer if the thickness is greater than 2 in.).

6.3 Future Study

The conclusion involves the overlay reinforcement for flexible pavements and the stress/strain absorbing interlayer for rigid pavements. The author derived this conclusion based on the mechanism and cause of RC as well as the overall structural capacity of the pavement structure. The two recommended methods are mitigation approaches rather than specific types of mitigation methods because there are numerous manufacturers dealing with different materials, strength, and cost of their product. Cost is one of the most important decision parameters. The cost of products, installation, and recycling will significantly affect the selection of RC mitigation method. Thus, the cost-benefit analysis for each mitigation method is essential prior to the selection of the final RC mitigation method.

APPENDIX: DESCRIPTIVE SURVEY RESULTS

In this section, detailed initial responses of the nationwide survey for current practices of the mitigation methods on flexible pavement are provided. These responses are based on the responses of state transportation agencies for each question.

1- Have you noticed reflective cracking on hot mix asphalt (HMA) overlays over flexible pavements when reflective cracking mitigation methods were not used?

It was a close-ended question; Yes or No. For this question, all the respondents selected “yes”. If the respondent’s answer was yes, then they were conducted through the other questions. Otherwise, they could not continue the survey.

2- In this case, what's the typical thickness of the HMA overlay (Inches)? (Open-ended)

Table A. 1 Typical Overlay Thickness

State	Typical Overlay Thickness
Illinois	2-4 inches
Alaska	2-3 inches
Idaho	0.15-0.2 inches
Iowa	4 inches in 2 lifts
West Virginia	1.5 inches
Washington	<6 inches
Missouri	3.75 Inches
Utah	1.5-3 inches
Ohio	1-3.5 inches
Indiana	1.5 inches
Arkansas	2-6 inches
Minnesota	1.5-3 inches
Nevada	2 inches
Georgia	1.5 inches
Wyoming	2 inches
Massachusetts	1.75 inches
Montana	0.15-0.2 Inches

3- How soon after placement of the overlay does the reflective cracking appear? (close-ended)

Table A. 2 Time after Construction to RC Appearance

State	RC Appearance Duration
Illinois	1-2 Year
Alaska	1-2 Year
Idaho	2-4 Year
Iowa	2-4 Year
West Virginia	1-2 Year
Washington	>4 Years
Missouri	2-4 Year
Utah	1-2 Year
Ohio	2-4 Year
Indiana	1-2 Year
Arkansas	N/A
Minnesota	1-2 Year
Nevada	>4 Years
Georgia	2-4 Year
Wyoming	2-4 Year
Massachusetts	2-4 Year
Montana	1-2 Year

4- Have you used any of the following to mitigate reflective cracking? If so, please comment on their field performance. (Close-ended)

Table A. 3 RC Mitigation Method Use Experiencing and Its Performance

State	Paving Fabrics/Geotextile	Reinforced HMA overlay(i.e. geogrids, steel, fiberglass)	Stress absorbing membrane inter layer (SAMI)	Strata-type inter layer	Crack-arresting layer	Increase overlay thickness	Others (please specify)
Illinois	Yes-Dissatisfied	No	Yes-Neutral	Yes-Neutral	Yes-Neutral	Yes-Neutral	Yes, ISAC-Neutral
Alaska	Yes-Satisfied	No	No	No	No	No	No
Idaho	Yes-Neutral	Yes-Satisfied	Yes-Satisfied	No	No	Yes-Satisfied	No
Iowa	Yes-Dissatisfied	No	No	Yes-Satisfied	No	No	Yes, Cold in place Recycling-No comment
West Virginia	Yes-Neutral	No	No	No	No	Yes-Satisfied	No
WASHINGTON	YES-DISSATISFIED	NO	YES-NEUTRAL	YES-DISSATISFIED	NO	YES-SATISFIED	NO

State	Paving Fabrics/Geotextile	Reinforced HMA overlay(i.e. geogrids, steel, fiberglass)	Stress absorbing membrane inter layer (SAMI)	Strata-type inter layer	Crack-arresting layer	Increase overlay thickness	Others (please specify)
Missouri	Yes-Neutral	No	Yes-Dissatisfied	Yes-Dissatisfied	No	Yes-Satisfied	Yes, Fiberglass joint treatment-Dissatisfied
Utah	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Neutral	Yes-Neutral	Yes, CIR interlayer-Neutral
Ohio	Yes-Satisfied	No	Yes-Dissatisfied	No	Yes-Neutral	No	No
Indiana	Yes-Dissatisfied	No	Yes-Neutral	Yes-Neutral	Yes-Neutral	Yes-Neutral	No
Arkansas	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Dissatisfied	No
Minnesota	Yes-Dissatisfied	Yes-Dissatisfied	Yes-Neutral	Yes-Dissatisfied	Yes-Neutral	Yes-Dissatisfied	No

State	Paving Fabrics/Geotextile	Reinforced HMA overlay(i.e. geogrids, steel, fiberglass)	Stress absorbing membrane inter layer (SAMI)	Strata-type inter layer	Crack-arresting layer	Increase overlay thickness	Others (please specify)
Nevada	Yes-Satisfied	Yes-Satisfied	No	No	Yes-Satisfied	Yes-Neutral	No
Georgia	Yes-Neutral	Yes-Dissatisfied	Yes-Dissatisfied	No	Yes-Neutral	Yes-Neutral	Yes, Crack filling material-No Comment
Wyoming	Yes-Neutral	Yes-Neutral	Yes-Neutral	No	Yes-Neutral	Yes-Satisfied	Yes, Milling, Saw Cracks-Satisfied
Massachusetts	Yes-Neutral	No	Yes-Satisfied	Yes-Neutral	Yes-Neutral	Yes-Satisfied	Yes, Gap-Graded AR Pavements-Satisfied
Montana	No	No	No	No	Yes-Satisfied	No	No

5- Why were the above mitigation methods selected? (Open-ended)

Table A. 4 Explanation for Selecting the Mitigation Method

State	Reason of Selecting The Mitigation Method
Illinois	Various research experiments have been performed over the years to try to mitigate reflective cracking. Note that most of this has been done on HMA overlays of concrete pavements.
Alaska	rapid installation
Idaho	Research
Iowa	In most cases, the methods were selected on a trial basis to determine if the method's crack mitigation and net cost was better than previously used methods. Cold in-place recycling is not selected for crack mitigation, though it is a side benefit.
West Virginia	Tried paving fabrics...if placed properly, they seem to help some. Most are difficult to place. Some seem better than others - Haetelit shows promise. Thicker overlays to put some structure back in pavements seem to help. Have not used SMA although it appears to be excellent based on adjacent states performance (VA). Looking to use a modified base layer as a crack arresting layer over transverse construction joints (PCC) prior to placement of traditional 1.5" surface course for interstate this year for the first time. Also going to try and use a cape seal treatment over a cracked pavement for the first time this year.
Washington	Past experience. The perception is that the treatments added some benefit but we have no documentation.
Missouri	To slow localized deterioration due to water infiltration such as asphalt stripping at the joint and creating a direct path for water to the base and subgrade.
Utah	N/A
Ohio	We are doing in house research on chip seals as crack arresting layers
Indiana	Some old methods, others by persuasion of vendors to try.
Arkansas	In an attempt to retard reflection cracking
Minnesota	to some extent, marketing

State	Reason of Selecting The Mitigation Method
Nevada	The method selected is based on cost, project constraints and distress severity or extent. Paving fabrics and fiberglass are used in urban areas with vertical constraints such as curb and gutter. A crack-arresting layer consisting of a 3" Cold-in-place recycle or 1.5" a PBS stress relief layer have both been used to mitigate reflective cracking in rural areas. The crack-arresting layer is followed by a surface treatment or a PBS overlay depending on traffic levels.
Georgia	Use of fabric reinforcing strips requires a minimum of 2-inch overlay.
Wyoming	Existing pavement had consistently spaced, wide width cracks.
Massachusetts	Costs, experience or anticipated performance of "thinner" overlay pavements.
Montana	For a crack arresting layer, we have used cold in-place recycling about 0.3' deep. We select that since it has worked in the past.

6- What criteria were used to determine appropriate reflective cracking mitigation methods?

Table A. 5 Criteria for Selecting an Appropriate RC Mitigation Method

State	Visual survey	Field evaluation/ testing	Traffic level	Pavement structure
Illinois	Yes	Yes	Yes	Yes
Alaska	Yes	No	No	No
Idaho	Yes	Yes	No	Yes
Iowa	Yes	No	Yes	Yes
West Virginia	Yes	No	No	No
Washington	Yes	No	No	No
Missouri	Yes	No	No	Yes
Utah	Yes	Yes	Yes	Yes
Ohio	Yes	Yes	No	No
Indiana	Yes	Yes	Yes	Yes
Arkansas	Yes	Yes	Yes	Yes
Minnesota	Yes	Yes	No	No
Nevada	Yes	No	No	Yes
Georgia	Yes	Yes	Yes	Yes
Wyoming	Yes	No	No	No
Massachusetts	Yes	Yes	No	Yes
Montana	Yes	Yes	Yes	Yes

7- Based on field experience, which reflective cracking mitigation method has been the most successful in your state? (Close-ended)

Table A. 6 The Most Successful Mitigation Method

State	**The Most Successful RC Technique**
Illinois	Increased Overlay Thickness
Alaska	Paving fabrics/geotextiles
Idaho	Reinforced HMA overlay (i.e. geogrids, steel, fiberglass)
Iowa	Strata
West Virginia	Increased Overlay Thickness
Washington	Increased Overlay Thickness
Missouri	Increased Overlay Thickness
Utah	Other- CIR Interlayer
Ohio	Paving fabrics/geotextiles
Indiana	Increased Overlay Thickness
Arkansas	None
Minnesota	SAMI
Nevada	Crack Arresting layer
Georgia	Crack Arresting layer
Wyoming	Increased Overlay Thickness
Massachusetts	Other-Milling, SAMI + Thicker Overlay
Montana	Crack Arresting layer

8- When using the best performing mitigation method, what is the performance expectation? In other words, how much longer do you expect it to last before reflective cracks appear? (Open-ended)

Table A. 7 Life Expectation of the Best Performing Mitigation Method

State	Life Expectation of RC Mitigation Method
Illinois	Hope to delay by a year or 2 and also minimize the severity.
Alaska	4-5 years
Idaho	Hope to get 4 to 6 year improvement
Iowa	Timeframe is not defined, but would be a factor in determining the net cost (added cost of crack mitigation method - maintenance cost savings) of the method being evaluated.
West Virginia	So far the most used method has been thicker overlays and the general rule of one year per an inch HMA seems to apply. In some cases though possibly sooner.
Washington	WSDOT does not have a major problem with reflective cracking. We do not have documentation available. Our estimate is that the treatments provide an extra two years of performance.
Missouri	Some pavements experienced 10 years plus.
Utah	N/A
Ohio	We have used fabrics in only a few situations. It has been used successfully for the reduction of thermal cracking. We have seen fewer cracks and less severe cracks after ~5 years of performance.
Indiana	increase overlay may delay +/- 1 year per inch of thickness.
Arkansas	3 years
Minnesota	2 years (estimate)
Nevada	Results vary depending on climate, traffic levels, quality of construction and severity of distresses. Typically, cracks are mitigated or reduced for 5-15 years.
Georgia	An additional 2 to 4 years
Wyoming	More than 5 years.

State	Life Expectaion of RC Mitigation Method
Massachusetts	5 years of additional life. Your question shouldn't ask just when the first crack appears, but the extension in service life. if the crack treatment servies as a waterproof barrier, there are additional performance benefits to not permitting the water to enter the pavement structure.
Montana	Cold in-place recycling before overlaying probably keeps the reflective cracking from appearing indefinitely.

9- Prior to designing the HMA overlay for a flexible pavement, what pavement tests and measurements are conducted for designing appropriate reflective cracking mitigation techniques? (Close-ended)

Table A. 8 Tests to Evaluate the Existing Pavement before Overlaying

State	Falling weight deflectometer	Ground penetrating radar	Coring	Dynamic cone penetrometer	Visual survey	Traffic count/vehicle class	Laboratory testing
Illinois	No	No	No	No	Yes	Yes	No
Alaska	Yes	No	No	No	Yes	Yes	No
Idaho	Yes	Yes	Yes	No	Yes	Yes	No
Iowa	No	No	No	No	Yes	Yes	No
West Virginia	Yes	No	Yes	No	Yes	No	No
Washington	No	No	Yes	No	Yes	No	No
Missouri	-	-	-	-	-	-	-
Utah	Yes	No	Yes	No	Yes	Yes	Yes
Ohio	No	No	No	No	Yes	No	No
Indiana	Yes	No	Yes	No	Yes	Yes	No
Arkansas	Yes	No	Yes	No	Yes	Yes	No

State	Falling weight deflectometer	Ground penetrating radar	Coring	Dynamic cone penetrometer	Visual survey	Traffic count/vehicle class	Laboratory testing
Minnesota	No	No	No	No	Yes	No	Yes- pave tech van
Nevada	No	No	Yes	No	Yes	Yes	No
Georgia	No	No	Yes	No	Yes	Yes	No
Wyoming	Yes	No	Yes	No	Yes	No	No
Massachusetts	Yes	No	Yes	No	Yes	Yes	No
Montana	No	Yes	Yes	No	Yes	No	No

10- What treatment(s) are typically used to prepare the existing flexible pavement before placing the HMA overlay? (Close-ended)

Table A. 9 Typical Treatments on Flexible Pavements before Placing HMA Overlay

State	Surface repairs (e.g., crack sealing, patching, etc.)	Milling only	Milling and replace wearing surface (or inlay)	Hot-in place recycling and heater scarification	Full-depth reclamation	No treatment	Others (please specify)
Illinois	Yes	Yes	Yes	No	Yes	No	No
Alaska	No	No	Yes	No	No	No	No
Idaho	Yes	No	Yes	No	No	No	No
Iowa	Yes	Yes	Yes	No	No	No	Yes-cold in-place recycling
West Virginia	Yes	No	Yes	No	No	No	No
Washington	No	No	Yes	No	No	No	No
Missouri	Yes	Yes	Yes	Yes	Yes	Yes	No
Utah	No	Yes	Yes	No	Yes	No	Yes-mill and CIR

State	Surface repairs (e.g., crack sealing, patching, etc.)	Milling only	Milling and replace wearing surface (or inlay)	Hot-in place recycling and heater scarification	Full-depth reclamation	No treatment	Others (please specify)
Ohio	No	No	Yes	No	No	No	Yes- partial depth repairs or full depth depending on need.
Indiana	Yes	Yes	No	No	No	No	No
Arkansas	Yes	Yes	No	No	No	No	No
Minnesota	Yes	No	Yes	No	Yes	No	Yes-CIR
Nevada	Yes	No	Yes	No	No	No	No
Georgia	Yes	Yes	Yes	No	Yes	No	No
Wyoming	Yes	Yes	No	No	Yes	No	No
Massachusetts	Yes	Yes	Yes	No	Yes	Yes	No
Montana	Yes	Yes	No	No	Yes	Yes	Yes- sometimes cold-in place recycling

11- For HMA overlay design, do you use a design method/guideline or simply use a minimum thickness? (Typical/minimum thickness description: e.g., 5 inches of HMA – 2 inches of 12.5 mm PG 76-22 over PG 76-22 over 3 inches of 19 mm PG 64-22) (Close-ended)

Table A. 10 Overlay Design Method

State	Overlay Design Method
Illinois	AASHTO-based procedure or Asphalt Institute
Alaska	Mechanistic Design Method
Idaho	Department uses WINFLEX program developed by University of Idaho.
Iowa	AASHTO design method
West Virginia	Min Thickness based on Traffic, Field Testing, Pavement Condition
Washington	Min Thickness, Remove and replace the top lift of top down cracked HMA. Typical depth is 0.15'.
Missouri	Min Thickness based on Pavement Condition
Utah	Design method/Guideline
Ohio	For our multi-lane divided routes we use deflection based methodology based on the Area method in the most recent AASHTO Guide. For our two lane-lower volume rural routes we use a standard 1-1/4" to 3-1/2" mill and fill, based on the level of cracking/distress, and what has worked in the past, as well as traffic levels (ie:experience based)

State	Overlay Design Method
Indiana	DARWin ME, or other version of MEPDG
Arkansas	Design method/Guideline
Minnesota	Design method/Guideline
Nevada	AASHTO-93
Georgia	Guideline-Structural Number
Wyoming	Are transitioning to DARWin-ME
Massachusetts	1972 AASHTO Pavement Design Method (Modified per DOT research) or 1993 AASHTO Interim Design Guide
Montana	Min Thickness- Based on Traffic and Pavement Condition

12- What constitutes criteria for a successful reflective cracking mitigation method? (in terms of improved performance, percentage reflected cracks, or both); Example: 50% of the reflective cracks appear after two years. (Open-ended)

Table A. 11 Expectation from an Applied Mitigation Method

State	Life Expectation
Illinois	N/A
Alaska	50% of the reflective cracks appear after two years
Idaho	Double the time between the mitigation section and a control section as to when reflective cracks reappear.
Iowa	No criteria established
West Virginia	We do not really have true established performance criteria at this time. But looking to develop some. Have started rewriting our HMA specs to include more in place end result specs for visual distress, surface irregularities, joint construction, etc.
Washington	N/A
Missouri	A combination of both. Some treatments have resulted in reduced frequency of cracking while increasing in severity.
Utah	N/A
Ohio	We do not currently use a standard mitigation method. But are evaluating the use of a chip seal interlayer
Indiana	No method of measuring success or not.
Arkansas	30% or less in 3 years
Minnesota	not a specific target
Nevada	Minimal cracking after 5 years
Georgia	No objective criteria established currently. Research underway.
Wyoming	Less severity (width) of resulting crack and delayed reflection.
Massachusetts	80% of cracks delayed for 5 years.
Montana	N/A

13- Do you consider life-cycle cost for each mitigation method? (Close-ended)

Table A. 12 Considering Life Cycle Analysis in Selecting the Method or Treatment

State	Life Cycle Cost Analysis
Illinois	No
Alaska	No
Idaho	No
Iowa	No
West Virginia	No
Washington	Yes
Missouri	No
Utah	Yes
Ohio	No
Indiana	Yes
Arkansas	No
Minnesota	No
Nevada	yes
Georgia	No
Wyoming	No
Massachusetts	Yes
Montana	No

14- How much is the unit cost of the method (per lane-mile)? (Open-ended)

Table A. 13 Unite Cost of the Selected Method

State	Unit Cost of the selected Method
Illinois	N/A
Alaska	N/A
Idaho	N/A
Iowa	N/A
West Virginia	Typical contract cost for two-lane secondary routes on the order of about $100,000 per lane per mile. For interstate four-lane routes not too much different, but a little more in some cases due to higher grade of materials used.
Washington	WSDOT uses $240 K per lane mile. This cost is fully loaded, preliminary engineer, construction engineering, taxes and contingencies.
Missouri	N/A
Utah	N/A
Ohio	Chip seal interlayer is fairly low cost ~$2/sy. Fabrics can be pretty expensive and would only be used where thermal cracking is pervasive and controls the time to resurface.
Indiana	N/A
Arkansas	unknown / highly variable
Minnesota	varies
Nevada	N/A
Georgia	Pavement reinforcing fabric and 3” PBS--$195,585 per lane mile 2. 1.5” type 3, 2” PBS--$171,165 3. 3” CIR, 2” PBS--$265,307 4. 3” CIR and Chip Seal--$173,488
Wyoming	unknown
Massachusetts	N/A
Montana	Mill, SAMI & HMA overlay = $115K per lane mile

REFERENCES

Amini, F. (2005). Potential Applications of Paving Fabrics to Reduce Reflective Cracking, (February).

Arif Chowdhury, Joe W. Button, and R. L. L. (2009). Tests of HMA Overlays Using Geosynthetics to Reduce Reflection Cracking, *7*(2).

Asphalt rubber usage guide. (2003)., (January).

Baek, J., Al-Qadi, I. L., Xie, W., & Buttlar, W. G. (2008). In Situ Assessment of Interlayer Systems to Abate Reflective Cracking in Hot-Mix Asphalt Overlays. *Transportation Research Record: Journal of the Transportation Research Board*, *2084*(-1), 104–113. doi:10.3141/2084-12

Beach, P. (2005). Experimental Project Status Report, 12–15.

Bennert, T. (2009). A Rational Approach to the Prediction of Reflective Cracking in Bituminous Overlays for Concrete Pavements.

Bennert, T., & Maher, A. (2007). Evaluation of Current State of Flexible Overlay Design for Rigid and Composite Pavements in the United States. *Transportation Research Record*, *1991*(1), 97–108. doi:10.3141/1991-12

Bennert, T., Worden, M., & Turo, M. (2009). Field and Laboratory Forensic Analysis of Reflective Cracking on Massachusetts Interstate 495. *Transportation Research Record: Journal of the Transportation Research Board*, *2126*(-1), 27–38. doi:10.3141/2126-04

Blankenship, P., Iker, N., & Drbohlav, J. (2004). Interlayer and Design Considerations to Retard Reflective Cracking. *Transportation Research Record*, *1896*(1), 177–186. doi:10.3141/1896-18

Carmichael, R. F. (FRANK)III A. M. L. M. (1988). Synthesis and Literature Review of Nonwoven Paving Fabrics, (99).

Chen, D., Won, M., Scullion, T., & Bilyeu, J. (n.d.). Minimizing Reflective Cracking With Applications of the Rolling Dynamic Deflectometer and Overlay Tester, 3–14.

Chen, Y. (2012). EVALUATION OF ASPHALT RUBBER MEMBRANCE INTERLAYER (ARMI) USING THE UNIVERSITY OF FLORIDA ' S COMPOSITE SYSTEM INTERFACE CRACKING (CSIC) TEST, (May).

Cleveland, G. S., Button, J. W., & Lytton, R. L. (2002). GEOSYNTHETICS IN FLEXIBLE AND RIGID PAVEMENT, *7*(2).

Dempsey, B. J. (2006). INTERLAYER STRESS ABSORBING COMPOSITE (ISAC) FOR MITIGATING REFLECTION CRACKING IN ASPHALT CONCRETE, (94).

DeVille, B. (2006). Decision Trees for Business Intelligence and Data Mining: Using SAS Enterprise Miner. SAS Institute Inc. Cary, NC, USA

Fujie Zhou, Sheng Hu, Xiaodi Hu, and T. S. (2009). FHWA / TX-09 / 0-5123-3 MECHANISTIC-EMPIRICAL ASPHALT OVERLAY THICKNESS DESIGN AND ANALYSIS SYSTEM November 2008 Resubmitted : February 2009 Resubmitted : July 2009 Published : October 2009 Fujie Zhou , Sheng Hu , Xiaodi Hu , and Tom Scullion Report 0-512, *7*(2).

Gayle, N., & Helen, W. (1988). Polymer Modified Bitumen: Laboratory Evaluation, Construction Guidelines and Field Experience.

Greene, J. (2012a). State of Florida Department of Transportation Effect of Asphalt Rubber Membrane Interlayer (ARMI) on Instability Rutting and Reflection Cracking of Asphalt Mixture, (September).

Greene, J. (2012b). State of Florida Department of Transportation Effect of Asphalt Rubber Membrane Interlayer (ARMI) on Instability Rutting and Reflection Cracking of Asphalt Mixture, (September).

Hicks R, Seeds SB, Peshkin DG. (2000). Selecting a Preventive Maintenance Treatment for Flexible Pavements, Foundation for Pavement Preservation, McLean.

Johanns, M., & Craig, J. (n.d.). Pavement Maintenance.

Loria, L., Sebaaly, P. E., & Hajj, E. Y. (2008). Long-Term Performance of Reflective Cracking Mitigation Techniques in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, *2044*(-1), 86–95. doi:10.3141/2044-10

Mixes, D. (2007). CHAPTER 10 THIN MAINTENANCE OVERLAYS, *I*.

Sholar, G. A., & Moseley, H. L. (2006). Evaluation of Segregation for Top-Down, (October).

State of Florida Department of Transportation Asphalt Rubber Membrane Interlayer (ARMI). (2011)., (February).

State of Florida Department of Transportation Crack Relief. (2012)., (August).

Symons, M., & Herrin, S. (n.d.). Technical Guide AAPTP 05-04 Techniques for Mitigation of Reflective Cracks, (217).

Thompson, M. (2008). ROAD REFLECTIVE CRACKING SYSTEM UNDER COLD CLIMATIC CONDITIONS , EVALUATION AND STUDY OF THE FIBER-REINFORCED EMULSION MEMBRANE Martin Thompson Midland Asphalt Materials Inc . International Symposium on Asphalt Emulsion Technology , ISAET, (September), 1–20.

Von Quintus, H. L., Mallela, J., Lytton, R. (2003). TECHNIQUES FOR MITIGATION OF REFLECTIVE CRACKS. *FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE*, (April 2010).

Wang, K.; Hu, J.; Ge, Z. (2008). *Material Thermal Input for Iowa Materials*.

Way, G. B. (1990). Flagstaff I-40 Asphalt Rubber Overlay Project Nine Years of Success.

Woo, W. J., Ofori-abebresse, E., Chowdhury, A., Kraus, Z., Martin, A. E., & Glover, C. J. (2007). Polymer Modified Asphalt Durability in Pavements, *7*(2).